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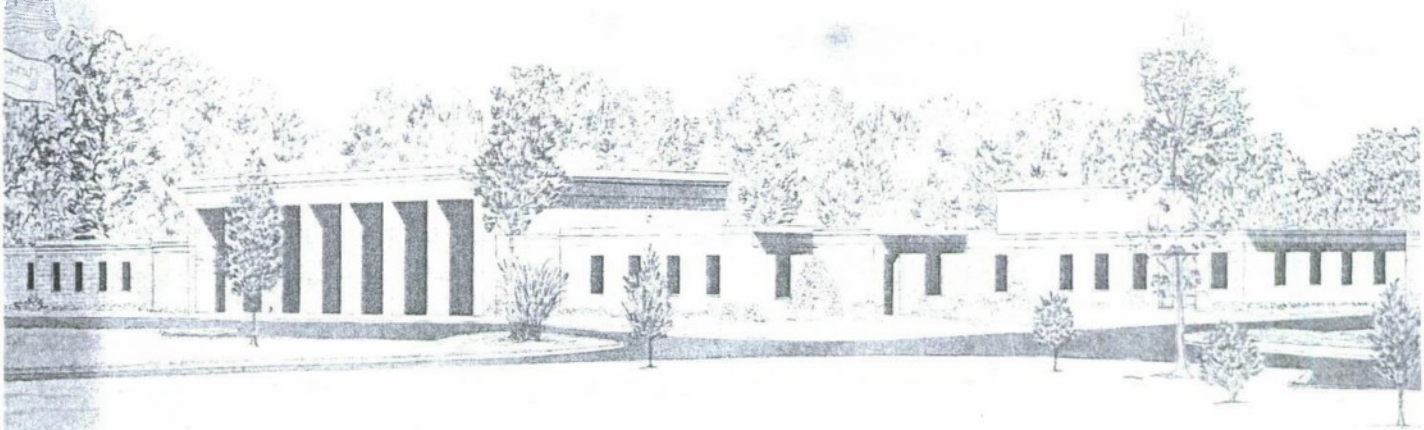
TECHNICAL REPORT N-72-6

OPERATION MINE SHAFT

MINERAL ROCK EVENT, FAR-OUT GROUND MOTIONS FROM A 100-TON DETONATION OVER GRANITE

by

D. W. Murrell



April 1972

Sponsored by U. S. Army Engineer Division, Huntsville

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

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ABSTRACT

The objectives of this study were to measure all ground motions in the outrunning region produced by the Mineral Rock Event of Operation Mine Shaft. The Mineral Rock Event was a duplication of the Mine Ore Event of the same series, and was a 100-ton sphere of TNT placed with the center of gravity 0.9 charge radius (about 7.2 feet) above the ground surface.

Accelerometers and velocity gages were installed from 200 to 500 feet from ground zero at depths of 2, 10, and 18 feet. Time histories of all successfully recorded gages are presented in Appendix A along with integrals of each record.

The outrunning acceleration data were partially obscured by a cable noise problem. This noise was blast overpressure-induced and unfortunately was present during the significant outrunning motion onset, i.e., before airblast arrival at the gage locations. Although these data are limited, they are discussed along with the outrunning velocity data. Airblast-induced motions are treated in detail.

Vertical airblast-induced accelerations were found to attenuate rapidly with distance and depth from the maximum downward acceleration of 32 g's at the 200-foot range and 2-foot depth. These accelerations were correlated with overpressure, and, for the 2-foot depth, acceleration-to-overpressure ratios averaged 0.2 g/psi, which is considerably less than for a similar detonation over soil.

Vertical particle velocities also attenuated with distance and depth from the maximum value of 1.3 ft/sec at the 200-foot range and 2-foot depth. Horizontal velocities followed much the same pattern, with a peak value of 2 ft/sec at the same location. Outrunning motion was noted on all horizontal velocity gage records. For the vertical component, outrunning motion was not apparent at the 250-foot range, but was of significant magnitude at the 500-foot range.

Vertical downward displacements of a high confidence level were limited to the 250-foot range and were found to be 0.0060 to 0.0075 foot. Horizontal displacements were successfully computed from acceleration and velocity records, and at the 250-foot range were three to four times as large as the vertical displacements.

PREFACE

This report describes an experiment conducted by the U. S. Army Engineer Waterways Experiment Station (WES) as a part of Operation Mine Shaft. This study was sponsored by the Research Branch of the Huntsville Division, U. S. Army Corps of Engineers (HND). Operation Mine Shaft itself was conducted under the auspices of the Defense Nuclear Agency (DNA), with the WES having direct technical supervision.

This study, designated Project SX30223, was conducted under the supervision of Messrs. G. L. Arbuthnot, Jr., Chief, Nuclear Weapons Effects Division, L. F. Ingram, Chief, Physical Sciences Branch and Technical Director for Mine Shaft, and J. D. Day, Chief, Blast and Shock Section. Project personnel were Messrs. D. W. Murrell, Project Engineer and author of this report, W. M. Gay, C. M. Wright, and F. L. Switzer, all of the Blast and Shock Section, and Messrs. L. T. Watson, F. P. Leake, B. E. Beard, G. H. Williams, and C. E. Tompkins of the Instrumentation Services Division, WES.

The author acknowledges the able assistance rendered by the WES Concrete Division personnel, under Mr. D. M. Walley, who performed the grouting work, and Soils Division personnel, under Mr. Henry McGee, who drilled all instrument holes.

COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE, were Directors of WES during the investigation and the preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows.

Multiply	By	To Obtain
inches	25.4	millimeters
feet	0.3048	meters
miles	1.609344	kilometers
pounds	0.4535924	kilograms
ounces	23.34952	grams
tons (2,000 pounds)	0.907185	megagrams
pounds per square inch	6.894757	kilonewtons per square meter
pounds per cubic foot	16.0185	kilograms per cubic meter
feet per second	0.3048	meters per second

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The objective of this study was to obtain and analyze ground motion measurements in the outrunning region for a high explosive (HE) surface burst over rock.

1.2 BACKGROUND

Rational design of missile launch and control systems requires knowledge of the free-field response of geological media to explosions which produce significant loadings of the ground surface. The phenomenon of outrunning ground motion is not well understood, and very little experimental data are available for design purposes. The Mine Shaft Series presented an excellent opportunity to supplement the meager amount of empirical data on hand. A rather limited program was undertaken on the first two events, Mine Under and Mine Ore (Reference 1), and the results suggested that a more ambitious program on Event Mineral Rock would be worthwhile. The charge weights and geometries for these events are given in Table 1.1.[1] While scaling of data from these HE tests to the nuclear case is less than exact, results of explosive tests can be extremely useful in verification of calculational techniques which are being developed for predicting ground shock from nuclear explosions.

1.3 GROUND MOTION PREDICTIONS

Since the amplitude and frequency ranges of instrument systems are limited, reasonably accurate predictions of ground shock phenomena are imperative for maximum data recovery and integrity. Theoretical prediction techniques currently available for above-ground detonations were developed primarily for superseismic ground shock in alluvial-type soils,

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[1] A table of factors for converting British units of measurement used in Table 1.1 and elsewhere in this report to metric units is given on page 8.

and extension of these to a hard rock environment was not deemed appropriate. Consequently, gage and recording system set ranges were selected on the basis of the limited far-out data acquired on Events Mine Ore and Mine Under and extrapolations of the close-in data from the Mine Ore Event (Reference 1). Predictions of peak motions for the parameters to be measured, i.e., horizontal acceleration (AH), vertical acceleration (AV), horizontal velocity (UH), and vertical velocity (UV), were made and are listed in Table 1.2 for the locations of interest.

TABLE 1.1 EVENTS IN WHICH OUTRUNNING MOTION DATA HAVE BEEN OBTAINED AT THE CEDAR CITY TEST SITE

Event	Date of Detonation	Yield	Charge Radius	Height to Center of Charge
		tons TNT	feet	feet
Mine Under	22 Oct 68	100	8	14.2
Mine Ore	12 Nov 68	100	8	7.2
Mineral Rock	8 Oct 69	100	8	7.2

TABLE 1.2 GROUND MOTION PREDICTIONS

Peak predicted values are downward (negative) values for vertical motions and outward (positive) values for horizontal motions. AV--vertical acceleration; AH--horizontal acceleration; UV--vertical velocity; UH--horizontal velocity.

Distance	Depth	Peak Predictions			
		AV	AH	UV	UH
feet	feet	g's	g's	ft/sec	ft/sec
200	2	25	25	a	a
	18	12	12	a	a
250	2	18	18	0.3	0.7
	10	13	13	0.2	0.5
	18	8	8	0.1	0.2
300	2	10	10	a	a
	10	7	7	a	a
	18	4	4	a	a
400	2	5	5	a	a
	10	3	3	a	a
	18	2	2	a	a
500	2	3	3	0.06	0.14
	10	2	2	a	a
	18	1	1	a	a

[a] Not measured.

CHAPTER 2

PROCEDURE

2.1 DESCRIPTION OF TEST SITE AND EVENT

The site of the Mine Shaft Series was in the Three Peaks area of southwestern Utah, roughly 8 miles northwest of Cedar City. The Mineral Rock Event was a 100-ton TNT sphere whose radius was approximately 8 feet and whose center of gravity was 7.2 feet (0.9 charge radius) above the ground surface. The event was detonated on 8 October 1969.

The test site itself was an iron-rich intrusion covered with a thin layer of sandy silt and somewhat weathered rock having a maximum surface relief of approximately 4 feet (Reference 2).

A detailed presentation of the rock properties is found in Reference 3. Briefly, the rock was classified as a tonalite according to the system of Shand (Reference 4), and results of laboratory analysis of the rock indicated a specific gravity of 2.6, a laboratory specimen compression wave velocity of 13,000 ft/sec, a porosity of 5.0 percent (relatively high compared to granite, dolomite, etc.), and nonlinear hysteretic stress-strain behavior. Refraction seismic surveys (Reference 5) conducted in the field showed generally lower seismic velocities than were obtained with the laboratory specimen. These lower velocities were found to be related to the direction of the major joint systems, which occurred predominately in a north-south direction. Seismic velocities of 9,700 to 12,200 ft/sec were observed on traverses parallel to the jointing (north-south), and from 8,000 to 9,400 ft/sec transverse to the joints (east-west).

2.2 INSTRUMENTATION LAYOUT

Thirty-six ground motion gages were installed for this project, including 28 accelerometers and 8 particle velocity gages. These gages were installed at 14 locations ranging from 200 to 500 feet from ground zero (GZ) and at depths of from 2 to 18 feet. The gage layout is presented in Table 2.1 and is shown graphically in Figure 2.1.

All gage locations were along a single radial line which lay roughly E 10° S of GZ. This line was an extension of the easterly gageline

instrumented for the close-in measurement program (Reference 6) which covered the region from 40 to 110 feet from GZ. Actual gage locations were varied slightly from a true radial in order to maintain, as closely as possible, the desired distance from GZ and yet to locate the gages in a reasonably competent outcrop of rock which required a minimal removal of overburden.

The system of gage identification used in this report was designed to be self-explanatory, listing in order the distance from GZ, the gage depth, and gage type and orientation. The code consists of a three-digit number giving the horizontal distance in feet, a one- or two-digit number giving the depth below surface in feet, and a two-letter code indicating the gage type and orientation. Gage types are broken down into accelerometers, coded as A, and velocity gages, represented by U. V represents vertical and H horizontal for the gage orientation. Thus for example, Gage 250-10-AH was a horizontal accelerometer located 250 feet from GZ and at a depth of 10 feet.

2.3 INSTRUMENTATION

<u>2.3.1 Gages and Calibration</u>. Of the 28 accelerometers installed for this study, 18 were Endevco Model 2262 semiconductor strain gage types, 8 were Statham Model A69TC gages, and 2 were Consolidated Electrodynamics Corporation (CEC) Model 4-202 strain gage models. The Endevco gages are undamped and have a natural frequency of 31 kHz. The Statham and CEC gages are damped to 0.7 times critical and have natural frequencies of 230 to 500 Hz, depending on range.

The particle velocity gages were a commercially available CEC version of the Sandia Corporation Model DX-B (Reference 7). This gage, developed under a Defense Atomic Support Agency (now Defense Nuclear Agency) contract, is a greatly overdamped mechanically integrating accelerometer. With various modifications for individual users, it is the "standard" particle velocity gage for ground shock measurements, and has proved reliable on a number of field experiments.

All gages were calibrated in-house at the U. S. Army Engineer Waterways Experiment Station (WES). All accelerometers were calibrated

statically on a spin table with proper cable lengths attached. Calibration resistors were then selected for each gage which gave an output of known acceleration when shunted across an arm of the bridge circuit.

The velocity gages were calibrated by allowing the seismic mass (a pendulum) to swing through its arc under the pull of gravity. A calibration curve was produced with a slope of 1 g for horizontal gages and 2 g's for vertical gages. Calibration resistors were selected which, when shunted, gave an output equivalent to a known velocity.

Calibration resistors were manually shunted, and outputs were recorded just prior to shot time, in case of failure of the automatic stepping circuit. At 30 seconds before shot time, all resistors were again shunted, this time automatically.

2.3.2 Recording System. Signal conditioning equipment for the accelerometers consisted of operational amplifiers designed and fabricated by WES. These amplifiers are solid state units having a frequency response of 0 to 10 kHz.

CEC 1-113B (System D) carrier-demodulator amplifiers were used with velocity gages. These units have a frequency response of 600 Hz when terminated with the design load of roughly 70 ohms (a galvanometer). On the Mineral Rock Event, however, the System D's were used to feed a tape driver amplifier, which is a high-impedance load, cutting the frequency response to about 100 Hz.

All data were recorded on CEC VR-3300 FM magnetic tape recorders. Twelve channels of data were recorded on each machine, along with a reference track and IRIG B time code.

All signal conditioning and data recording equipment was housed in two recording vans located some 3,000 feet from GZ. These vans were parked behind timber and earth revetments to provide protection from airblast and ejecta. Figure 2.2 shows the recording van area; the view is toward GZ and the protective revetments can be seen in the background.

2.3.3 Data Reduction. All data recorded in the field were of analog form on FM magnetic tape. These were digitized at the rate of 24 kHz on an analog-to-digital converter at WES. The digital data were then processed through a GE 400 digital computer which performed integrations and, where

necessary, baseline corrections, and were then plotted automatically by an on-line plotter.

2.4 FIELD OPERATIONS

Field operations for this project began immediately following the Mineral Lode Event, which was detonated on 5 September 1969. All field operations, benefited by good weather and working conditions, proceeded smoothly, and the project was ready on 29 September 1969, 10 days preshot.

2.4.1 Instrument Cables. Cable runs of 50-pair telephone-type cable were used for 2,700 feet from the recording van area toward GZ. These cables had been installed for Events Mine Under and Mine Ore and were found to be serviceable. About 300 feet from GZ, a junction box was installed, and additional multipair cable was run to the far-out motion gageline where a second junction box was installed. From this point, individual four-conductor cable was run to each gage. All individual gage cables destined for a given location were then bundled together and were protected by pipe insulation of 1/2-inch wall thickness. Cables between junction boxes and between the second junction box and instrument holes were placed in trenches 12 to 18 inches deep in the soil overburden. Where subsurface rock prevented this, the cable was bedded in dry sand and covered with sandbags and native material.

2.4.2 Gage Installation. All ground motion gages scheduled for a particular location were installed in a single aluminum canister. The canister was constructed of 5-inch-outside-diameter by 1/2-inch-wall-thickness aluminum tubing, with end caps of 1/2-inch aluminum plate. The bottom end cap had an aluminum gage mounting block welded in place. A placement stem was attached to the top cap. Canisters were potted with paraffin after gage installation to dampen gage mount vibration and seal out moisture. Overall canister length, not counting placement stem, was 10 inches, and weight was 17 pounds 2 ounces, giving a density of 171 pcf. This compares favorably with the average rock density of 162 pcf.

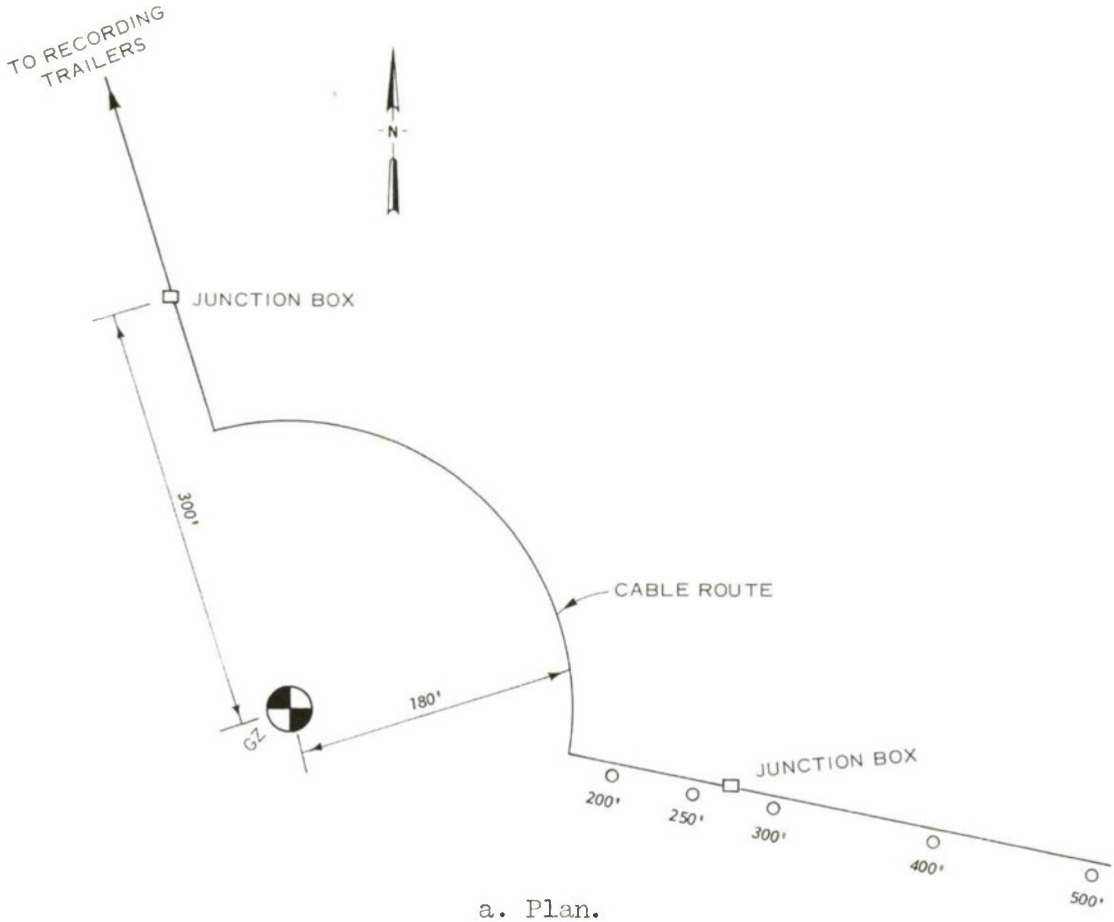
Figure 2.3a shows a canister bottom cap and gage mounting block with two velocity gages and two accelerometers installed. Figure 2.3b shows a typical assembled canister with placement stem attached.

Gage canisters were set in place using an aluminum placement tool, the bottom section of which contained a threaded coupling to fit the placement stem. After placement and orientation of a canister, grout designed to match the density and sonic velocity of tonalite was pumped until the canister was just covered. The grout was then allowed to set, the placement tubing was removed, and grout was pumped to a point just below the next canister location. The installation procedure was then repeated for this location.

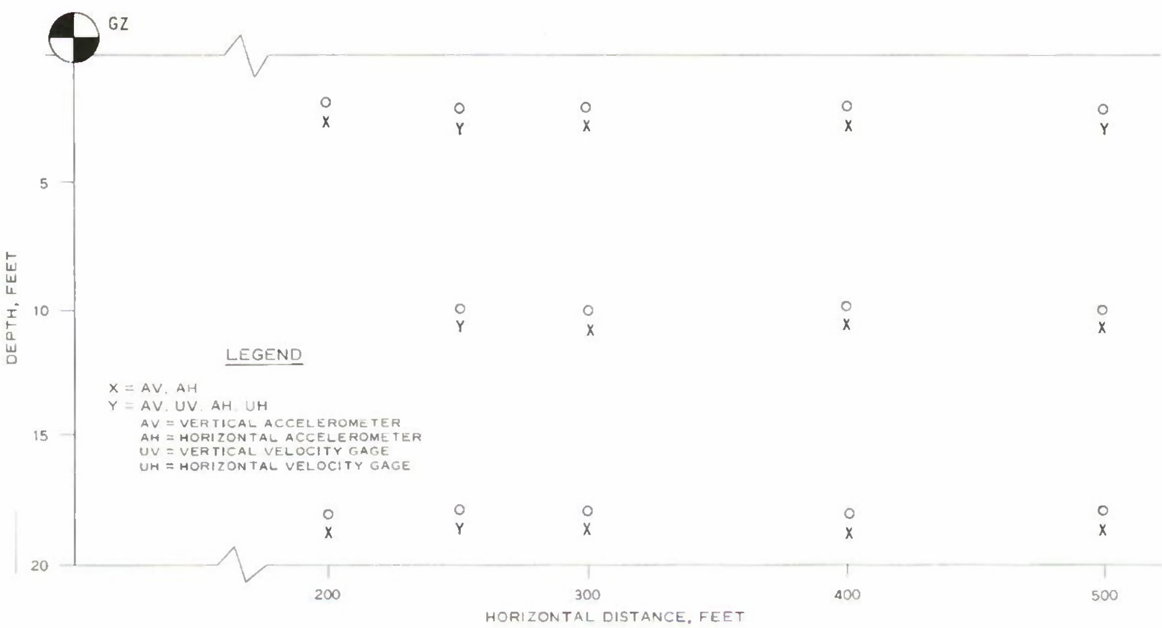
TABLE 2.1 GROUND MOTION GAGE LAYOUT

X denotes AV, AH; Y denotes AV, AH, UV, UH. AV--vertical acceleration; AH--horizontal acceleration; UV--vertical velocity; UH--horizontal velocity.

Horizontal Distance	Gage Array at Indicated Depth		
	2 feet	10 feet	18 feet
feet			
200	X		X
250	Y	Y	Y
300	X	X	X
400	X	X	X
500	Y	X	X



a. Plan.



b. Section.

Figure 2.1 Gage layout.

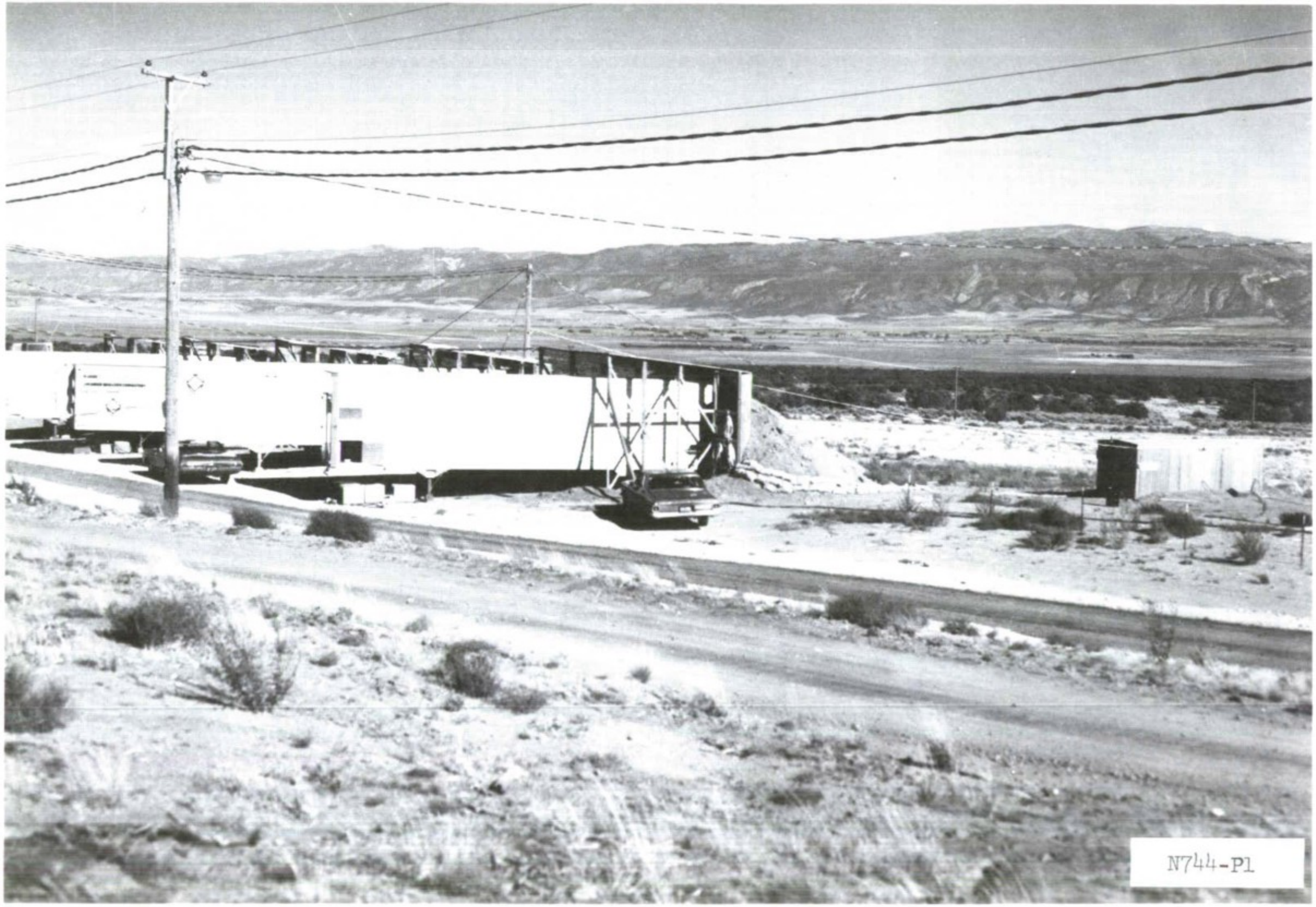
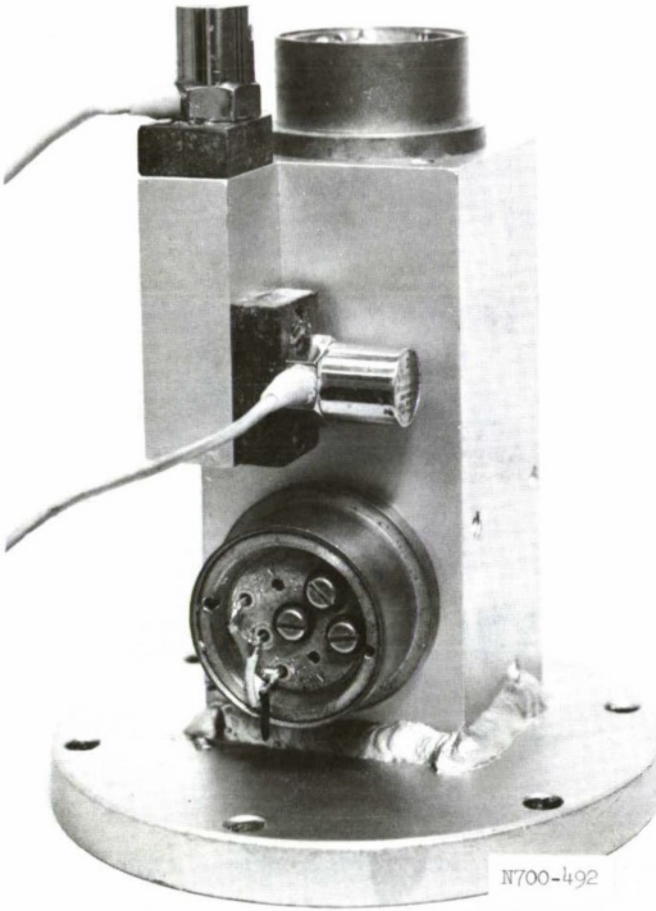


Figure 2.2 Recording van area.



a. Gage mount and gages.

b. Assembled gage canister.

Figure 2.3 Typical gage canister assembly.

CHAPTER 3

RESULTS

3.1 INSTRUMENT PERFORMANCE

All gages checked out satisfactorily after installation, and all were operational at shot time. Start signals were received at shot time, and calibration and recording equipment operated as programmed. The Detonation Zero pulse was received and recorded on all tape machines.

Of the 36 gages installed for the Mineral Rock Event, 34 responded to the ground shock. No data were received from Gages 500-2-UH and 500-10-AV. Seven particle velocity gages operated successfully and yielded data of excellent quality. The 27 accelerometers, however, were affected by electrical noise at 20 msec after detonation. This noise persisted for about 15 msec, and primarily affected records from the 300- and 400-foot ground ranges. Attempts to remove the noise by digital filtering were unsuccessful since the noise was within the frequency band of the ground shock data itself.

Some of the noise was removed by beginning data processing only after onset of the noise. Data processing was begun at 25 msec after detonation for data from the 300-foot range, at 35 msec for the 400-foot range, and at 45 msec for the 500-foot range. These times were selected in order to skip as much noise as possible yet insure that little or no data were lost. That no real, or at least measurable, data were thus removed is borne out by the shock arrival time of 29 msec for the horizontal velocity gage at the 250-foot range and 18-foot depth. The minimum arrival at the 300-foot range would then be about 33 to 34 msec, or well after data processing had begun. This procedure substantially improved the quality of record integrations by removing a large portion of the noise-induced baseline shift. Some effects of this noise are still present in the first and second integrals, however.

It is worth noting that onset of the noise coincides with airblast arrival at the portions of the gage cable line which lie closer to GZ than the gageline itself (see Figure 2.1). Since the pressures encountered could alter somewhat the electrical characteristics of the cable, the noise

was possibly shock generated. It remains unresolved, however, why the velocity data were not affected, since the ac carrier system should be more sensitive to capacitive changes induced by squeezing than the dc accelerometer circuits.

The 34 successfully recorded time histories are presented in Appendix A along with first and second integrals. The label in the upper right-hand corner of each record lists the event, gageline direction (east), and gage identification code, plus computer and data recall information. Marked on each record with an arrow labeled "AB" is the airblast arrival time at the surface above the gage.

Peak values of measured parameters and integrals are presented in Table 3.1.

3.2 ARRIVAL TIMES

Arrival times of ground motion were unfortunately obscured by noise except for four of the velocity gages and the two accelerometers at the 200-foot range and 18-foot depth. Arrival times for these gages are listed in Table 3.1. Both of the accelerometers showed initial response at 16.8 msec after detonation, indicating arrival of outrunning ground shock (the airblast arrived at this point some 24 msec after detonation). The average ground shock transmission velocity was 12,000 ft/sec to the 200-foot range, and is in fair agreement with the 13,000 ft/sec determined by laboratory compression wave velocity tests. Initial motion was detected on the horizontal velocity gages at the 250-foot range at 29, 30, and 32 msec for the 18-, 10-, and 2-foot depths, respectively, while airblast arrival at this point was about 40 msec, again indicating the presence of outrunning motion. Average shock transmission velocity from GZ to Gage 250-18-UH was then 8,500 ft/sec, which is considerably less than that calculated for the 200-foot station.

Outrunning motion was also noted at Gage 500-2-UV, where the arrival time was 62.4 msec, giving a transmission velocity of 8,000 ft/sec. The difference may be attributed, at least in part, to the difficulty in picking accurate arrival times for the velocity gages, which exhibit low

initial motions and long rise times. It is worth noting also that the 8,000- to 8,500-ft/sec velocities are in good agreement with data obtained on field seismic tests which reported velocities much less than those obtained on the laboratory specimens. It is also possible that rock jointing, which caused lower seismic velocities in the east-west direction than in the north-south direction, was locally most severe beyond the 200-foot range.

Figure 3.1 is a plot of airblast-induced-motion arrival times at the 2-foot depth and, where obtained, outrunning arrival times versus distance. The airblast-induced-motion arrival times are noted to agree well with the predicted airblast arrival itself and serve to substantiate the airblast predictions since arrival times for airblast were not reported beyond the 320-foot distance.

3.3 ACCELERATION

As mentioned previously, all acceleration channels were subjected, to some degree, to an extraneous electrical noise during the early portion of the ground motion. This noise obscured the outrunning ground motion and, at the 200- and 250-foot ranges, was superposed on the airblast-induced motions. Fortunately, the airblast-induced signals at these locations were of considerably greater amplitude than the noise signals. This can be seen from the first two traces in Figure 3.2. At the 300-foot and 400-foot stations, initiation of data processing was delayed, thus eliminating most of the noise. This process was used also at the 500-foot range; however, at this location signal amplitude was small enough that the noise is still quite apparent. The waveforms seen in Figure 3.2 are characteristic of near-surface vertical accelerograms in rock, i.e., a sharp downward spike of very short rise time (generally less than 1 msec) followed by oscillations and/or an upward pulse.

The record of Gage 500-2-AV shows a fairly well developed outrunning waveform, although the early portion is obscured. After noise cessation at about 105 msec, the oscillatory, relatively long-period pulse of outrunning motion is evident, with the downward spike at airblast arrival superposed at 153 msec. The downward acceleration due to airblast is noted to be of

larger magnitude and shorter duration than the immediately preceding outrunning signal. This was consistent throughout the array. Figure 3.3 is a plot of peak downward vertical acceleration versus distance for all three depths instrumented. Four vertical acceleration peaks measured at the 2-foot depth on Event Mine Ore are included, and are generally in good agreement with the Mineral Rock data.

Peak downward accelerations at the 2-foot depth are noted to attenuate rapidly with increasing distance. This suggests the use of a correlation based on downward acceleration-to-overpressure ratios, which has also been found effective for accelerations in soil (Reference 8). Figure 3.4 is a plot of this ratio versus overpressure for the five stations instrumented. Overpressures used in computing the ratios are listed in Table 3.2 (Reference 9).

For the first four stations, 200, 250, 300, and 400 feet, the downward acceleration-to-overpressure ratios are 0.16, 0.14, 0.24, and 0.20 g/psi, respectively. At the 500-foot range, the ratio drops off to 0.10, in contrast to the pattern of increasing ratios at lesser overpressures usually observed in soil. The 0.2-g/psi average ratio for the first four locations is considerably lower than the figure of 0.6 to 1.0 g/psi for similar pressure ranges noted for 100-ton detonations over soil (Reference 8). This is consistent with elastic theory, which gives an inverse relationship between acceleration and seismic velocity for a constant rise time of stress. The difference is not as great as the 10-fold difference that the seismic velocity ratio would suggest.

Attenuation of peak downward vertical acceleration with depth is also apparent from Figure 3.3 and is consistent throughout the horizontal array. Peak values at the 18-foot depth ranged from 22 to 38 percent of those at the 2-foot depth. This is in marked contrast to data in soil, where accelerations at a depth of 17 feet average about 7 percent of near-surface (1.5-foot) data. This fact emphasizes the effectiveness of an alluvial soil, such as encountered on the Distant Plain Series, as a filter of high-frequency motions, even though near-surface accelerations are larger at similar overpressures in soil.

Peak horizontal accelerations are plotted versus distance in Figure 3.5. The peak values plotted are peak outward accelerations neglecting apparent noise peaks. In most cases, the peak values can be attributed to passage of the airblast, with two obvious exceptions being Gages 500-2-AH and 500-10-AH. At these locations, the acceleration signature was dominated by an outrunning motion of both greater magnitude and considerably longer duration than the airblast-induced motion. A rapid attenuation with distance is again apparent, and, for the 2-foot depth, is about the same in rate as was noted for vertical accelerations. The peak horizontal accelerations themselves, however, are consistently only 40 to 60 percent of the vertical peaks.

Horizontal accelerations also attenuate sharply with depth. Most of the attenuation appears to occur in the upper 10 feet of rock, with generally only a small difference in peak values at 10- and 18-foot depths. This is in contrast to vertical measurements, where data at the 18-foot depth were consistently well below those at the 10-foot depth.

3.4 PARTICLE VELOCITY

The number of particle velocity gages installed for this project was unfortunately small, especially in view of the high quality data yielded. Integrals of acceleration records, especially the early portions, are somewhat suspect due to the noise problem. See, for example, the first integral of Gage 300-10-AH (Figure A.20) where integration of the noise produced a relatively spurious and erroneous initial velocity.

Figure 3.6 shows, for comparison, the three vertical velocity records from the 250-foot ground range. These records are typical of vertical velocities in the superseismic region, and indicate an absence of measurable vertical outrunning ground shock at this location. The records are characterized by an initially downward pulse of width which increases with depth, followed by an upward motion of nearly uniform duration. Also shown in Figure 3.6 is a composite vertical velocity record constructed from close-in data (Reference 6) from Mineral Rock which was obtained at distances of 40 to 110 feet from GZ. It is emphasized that the amplitudes indicated on the composite record are meaningless, even as a relative

indicator, since the amplitudes of various portions of the record are dependent on location. A striking similarity in wave shape is present, however, indicating that predominant features of the ground shock persist throughout the range of instrumentation. Of interest here is the increased width of the initial downward pulse for the far-out data, which follows the pattern set on close-in measurements. The initial downward pulse, for example, was only of 1.8-msec duration at the 40-foot range, and had increased to 4.8 msec at 110 feet, both at the 2-foot depth (Reference 6). The duration of this pulse had increased to 16 msec at the 250-foot location. The subsequent upward and downward oscillation does not appear to have been affected by either depth or distance and retained a nearly uniform period of 140 msec at all distances and depths instrumented for both close-in and far-out programs.

In contrast to the apparently superseismic waveforms of Figure 3.6, the outrunning vertical velocity of Gage 500-2-UV is shown in Figure 3.7. Here the motion is initially upward and is oscillatory, with the downward airblast-induced pulse superimposed on the outrunning motion at about 155 msec. The outrunning motion is both larger and of longer period than the airblast-induced pulse at this location, and the wave shows significant oscillation well beyond the airblast arrival. Since this record indicates that significant vertical outrunning motion was present at this range, it would be expected that similar motions would be observed at the 250-foot stations at corresponding times, i.e., about 30 msec. It is also apparent that the magnitudes and frequencies are well within the capability of the velocity gage. Significant horizontal outrunning motion was observed at the 250-foot range, as will be discussed later, so it must be concluded that the outrunning pulse, though present, had not developed a measurable (relative to airblast motion) vertical component at the 250-foot range.

Peak downward vertical particle velocity is plotted versus distance in Figure 3.8. Shown here are the four vertical velocity measurements along with integrals of vertical acceleration records. In all cases where velocity was measured directly, the peak downward motion was considerably less than that obtained from integrated accelerations. This is in keeping with results from previous tests, although the low-frequency response of the

velocity gage amplifiers, as used on this experiment, probably aggravated the problem.

For the most part, downward velocities plotted in Figure 3.8 are associated with passage of the airblast above the point in question, although outrunning motions no doubt exert some influence on the peaks. Phasing of the airblast relative to outrunning motion was important at Stations 500-2 and 500-18. For example, at Station 500-2, the airblast pulse was superposed on an upward cycle, and no net downward motion resulted. Peak downward motions for this station are consequently not associated with the airblast.

Vertical velocities, as did accelerations, attenuated sharply with distance, at about the same rate for the 2-foot depth as the airblast overpressure. Downward velocities at the 2-foot depth correlate well with pressure, and velocity-to-overpressure ratios range from 0.012 to 0.023 ft/sec/psi. This ratio is again less than has been observed for alluvial soils where ratios in this pressure region are about 0.05 ft/sec/psi (Reference 8).

Attenuation of the downward velocities with depth is less regular than was found for accelerations, and at the 300- and 400-foot ranges the deeper motions are greater than the shallow ones. This can probably be attributed, at least in part, to integration of noisy data. The three directly measured velocities at the 250-foot range, for example, do exhibit a decrease in amplitude with increasing depth, as might be expected. This reinforces their credibility, at least in relation to each other.

An average fit to the close-in velocity data is also shown in Figure 3.8. Most of the data fall in reasonable proximity to an extension of the close-in data, although several points appear to be rather high. It is clear that no gross anomalies in magnitudes are present, and this is in turn an indicator of data reliability.

Figure 3.9 shows horizontal particle velocity-time histories for the 250-foot range. The first of these, for the 2-foot depth, is marked by two features which depart from the pattern set by the two deeper stations. First is the double peak on the first outward pulse which was not noted at the deeper locations; however, it did appear on the acceleration integral

also (Figure A.7). The second anomalous occurrence is the series of fairly significant peaks at 160 to 180 msec after detonation. This was not apparent to any extent on the integrated acceleration, and is thought to be a gage malfunction. The remaining two records show a single smooth outward pulse of similar duration. The last plot on Figure 3.9 is a composite horizontal velocity waveform constructed from close-in data (Reference 6). The amplitude is again arbitrary. The period of this pulse averaged 50 msec, which appears slightly shorter than on the far-out data, although the difference is not great.

Figure 3.10 presents peak outward horizontal velocities versus distance for both direct measurements and integrals. Much better agreement is immediately noted between peak values obtained by the two methods than was found for vertical data. This follows the trend noted for close-in measurements and is probably due to the lower frequencies (longer initial pulses) for horizontal data which the velocity gages are better able to follow.

Attenuation with range is similar to that found for vertical data, and follows a projection of close-in measurements quite well. As a result, there appears to be approximately a one-to-one correspondence between horizontal and vertical peaks, at least within the data scatter. Attenuation with depth, although apparent, is not pronounced, and again is concentrated in the upper 10 feet of rock.

3.5 DISPLACEMENT

Vertical displacement peaks, as can be seen from Table 3.1, show considerable disparities between second integrals of acceleration and first integrals of velocity, and even between measurements at the same ground range. Consequently, no plot of vertical displacement versus distance was constructed. The three integrals of velocity measurements at the 250-foot range did produce displacements which were very consistent among themselves, ranging from 0.0060 foot at 18-foot depth to 0.0075 foot at 2-foot depth. This precision, together with the generally typical velocity waveforms from which they were derived, lends credence to the data at this point.

Peak horizontal displacements are plotted versus distance in

Figure 3.11, and with two readily apparent exceptions, plot nicely with a regular attenuation pattern. Very little attenuation with depth is seen in Figure 3.11, with a notable example being the data at 250-foot range where all six data points (three velocity integrals, three acceleration second integrals) all fall between 0.020 and 0.028 foot. The horizontal peak displacement values all seem to fall somewhat above the average fit to close-in data. It should be kept in mind, however, that the representative fit to the close-in data is an average, and data scatter would encompass the far-out peaks.

Using the data at the 250-foot range as representative values, it is seen that horizontal displacements at this range are three to four times larger than the vertical. Since peak velocities exhibited a one-to-one correspondence, the difference can be attributed to the longer durations of the horizontal particle velocities. This, in turn, is brought about by the fact that horizontal airblast and outrunning velocity pulses reinforce each other (both outward), thus tending to lengthen outward pulse duration, while destructive interference may occur in vertical displacements depending on placing of the airblast and outrunning signals.

TABLE 3.1 PEAK GROUND MOTION DATA

AV--vertical acceleration; AH--horizontal acceleration; UV--vertical velocity; UH--horizontal velocity. Positive motion is upward for vertical and outward for horizontal.

Distance	Depth	Gage Type	Arrival Time	Acceleration		Velocity		Displacement	
				Positive	Negative	Positive	Negative	Positive	Negative
feet	feet		msec	g's	g's	ft/sec	ft/sec	feet	feet
200	2	AV	--	23	32	0.14	1.4	a	0.03
		AH	--	16.4	19.2	1.9	0.48	0.059	b
	18	AV	16.8	4.9	7.1	0.37	0.88	a	0.016
		AH	16.8	4.8	2.4	1.4	0.52	0.04	b
250	2	AV	--	8.9	15.6	0.34	1.2	a	0.016
		UV	--		--	0.27	0.72	0.002	0.0075
		AH	--	10.0	3.0	1.4	0.50	0.028	b
		UH	32.0	--	--	1.2	0.40	0.026	b
	10	AV	--	3.1	4.0	0.26	1.2	a	0.052
		UV	--	--	--	0.28	0.43	0.002	0.007
		AH	--	3.2	2.2	0.96	0.42	0.027	b
		UH	30.0	--	--	0.85	b	0.026	b
	18	AV	--	2.2	2.8	0.39	0.62	0.005	0.012
		UV	--	--	--	0.28	0.34	0.003	0.006
		AH	--	4.6	1.8	0.76	0.15	0.023	b
		UH	29.0	--	--	0.60	0.22	0.019	b
300	2	AV	--	10.4	12.0	0.42	0.59	0.017	0.003
		AH	--	6.6	6.0	0.72	0.76	0.023	b
	10	AV	--	2.4	4.2	0.51	0.72	a	0.017
		AH	--	2.4	2.2	0.66	0.43	0.019	b
	18	AV	--	1.4	2.6	0.25	0.56	a	0.015
		AH	--	1.7	1.4	0.62	0.53	0.022	b
400	2	AV	--	6.0	6.0	0.34	0.42	0.001	0.006
		AH	--	2.4	2.5	0.48	0.35	0.014	b
	10	AV	--	3.0	2.4	0.70	0.72	0.014	0.018
		AH	--	1.4	1.1	0.22	0.40	0.009	0.008
	18	AV	--	2.0	1.5	0.38	0.59	0.001	0.014
		AH	--	0.88	1.0	0.18	0.62	0.007	0.019
500	2	AV	--	2.80	1.4	0.19	0.16	0.003	0.007
		UV	62.4	--	--	0.12	0.12	0.002	0.003
		AH	--	0.58	0.49	0.32	0.05	0.022	b
		UH	--	c	--	--	--	--	--
	10	AV	--	c	--	--	--	--	--
		AH	--	0.58	0.60	0.48	0.10	0.034	b
	18	AV	--	0.60	0.56	0.25	0.13	0.008	b
		AH	--	0.66	0.52	0.14	0.22	0.005	b

[a] No positive peak.
[b] No negative peak.
[c] No data.

TABLE 3.2 AIRBLAST OVERPRESSURES

Distance	Pressure	Remarks
feet	psi	
200	190	Predicted value
250	115	Airblast Line 1 (North)
300	49	Adjacent to ground shock instrument hole
400	30.3	Adjacent to ground shock instrument hole
500	15.0	Adjacent to ground shock instrument hole

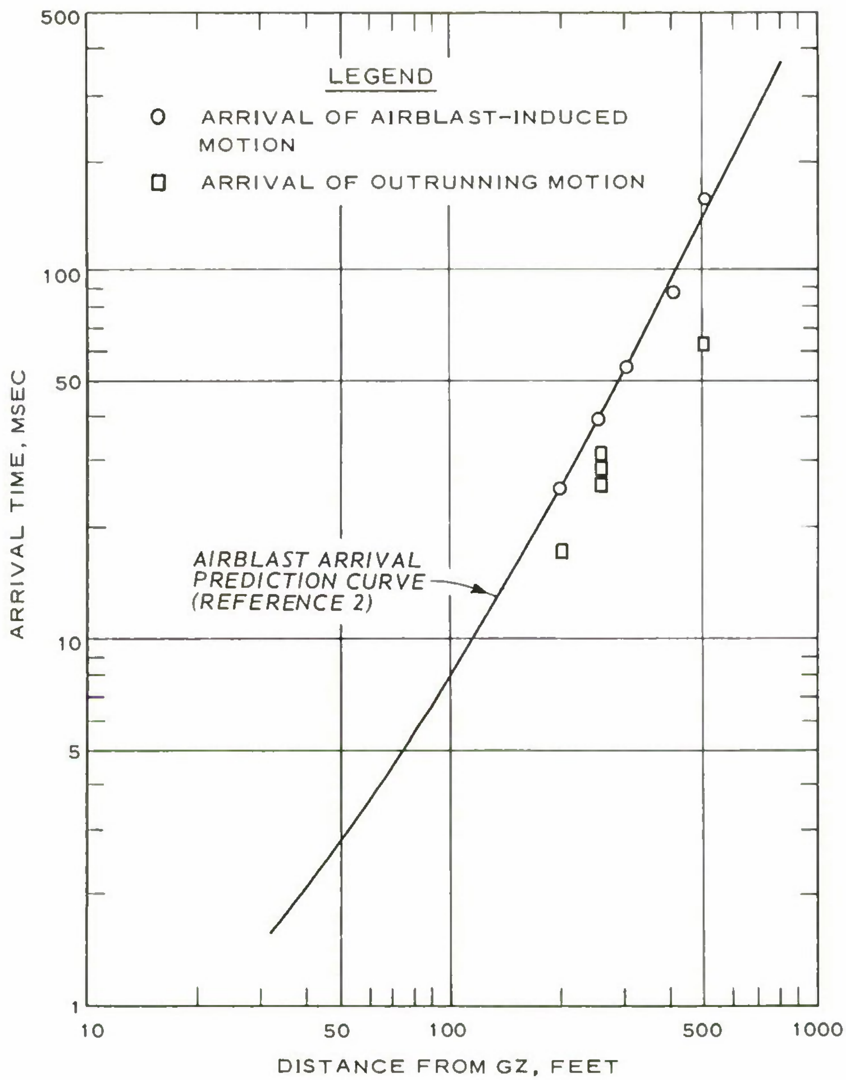


Figure 3.1 Motion arrival times at 2-foot depth.

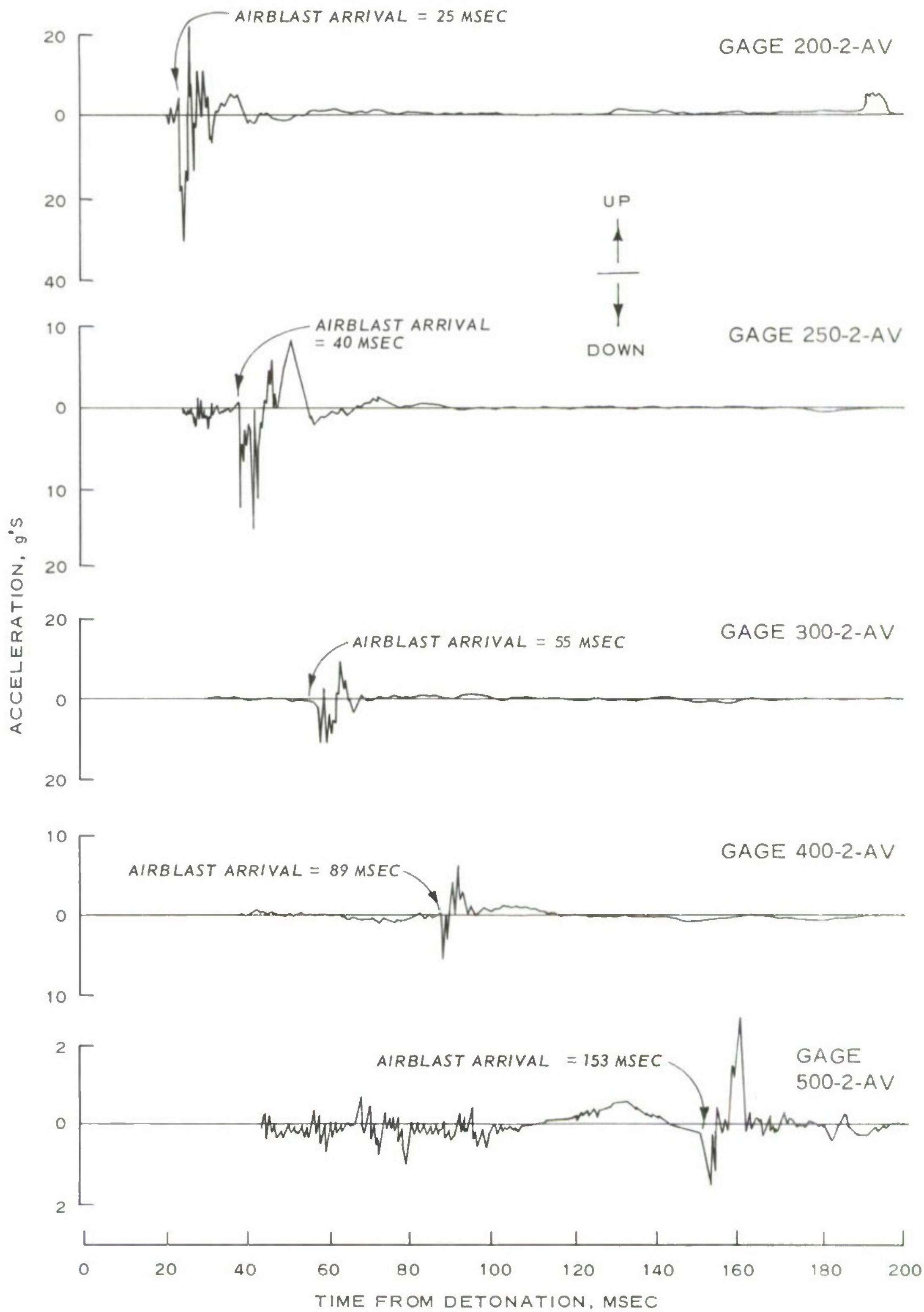


Figure 3.2 Vertical acceleration histories, 2-foot depth.

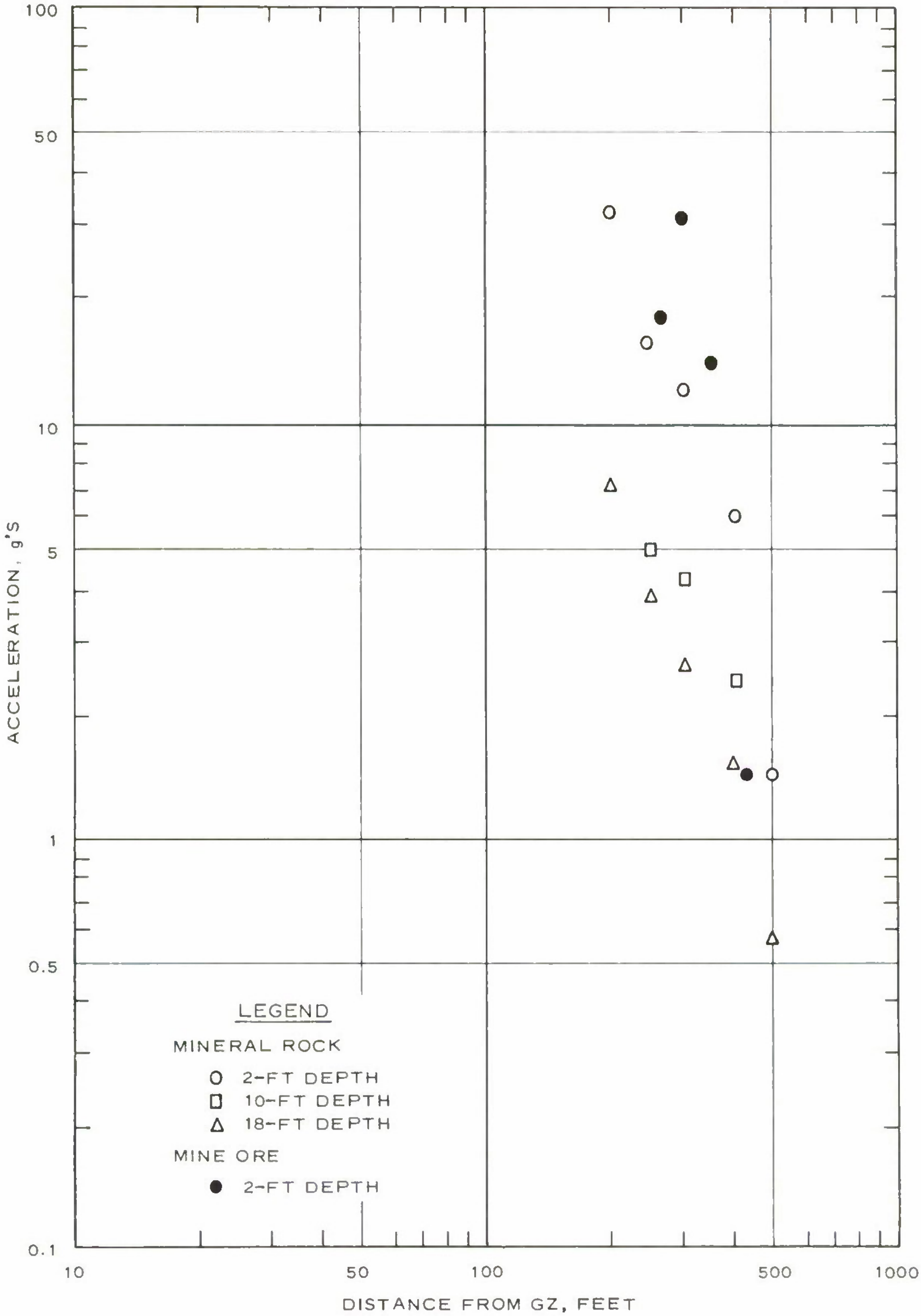


Figure 3.3 Peak downward vertical acceleration versus distance.

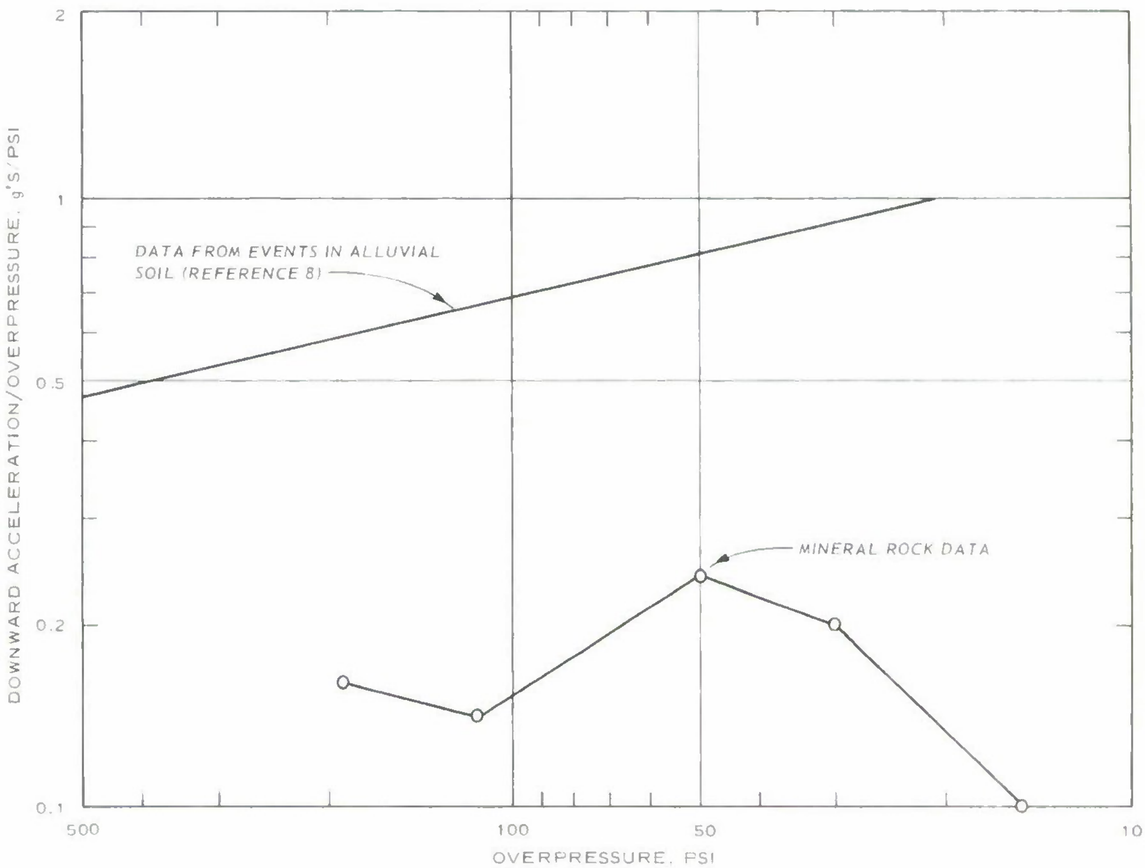


Figure 3.4 Acceleration-to-overpressure correlation.

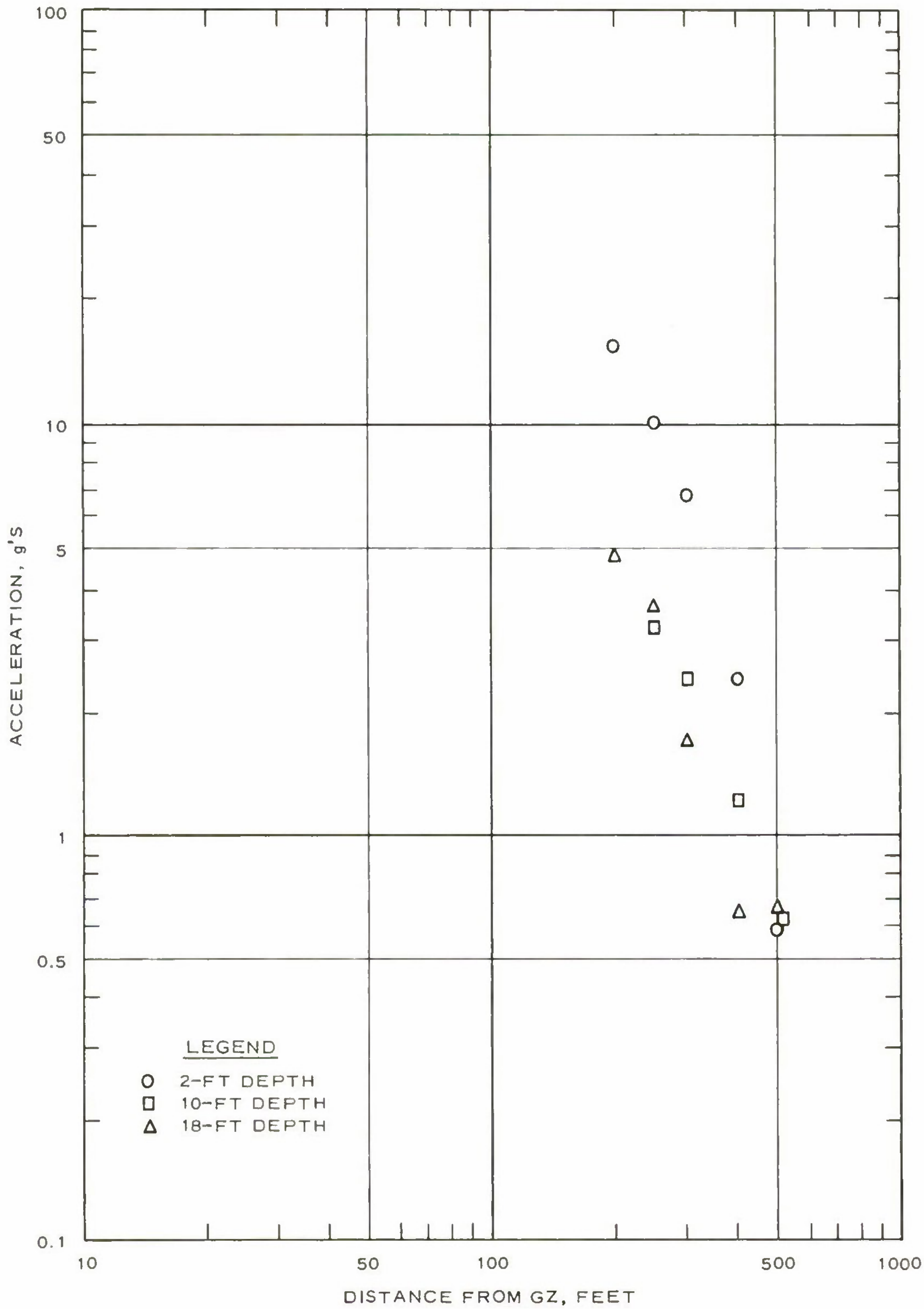


Figure 3.5 Peak horizontal (outward) acceleration versus distance.

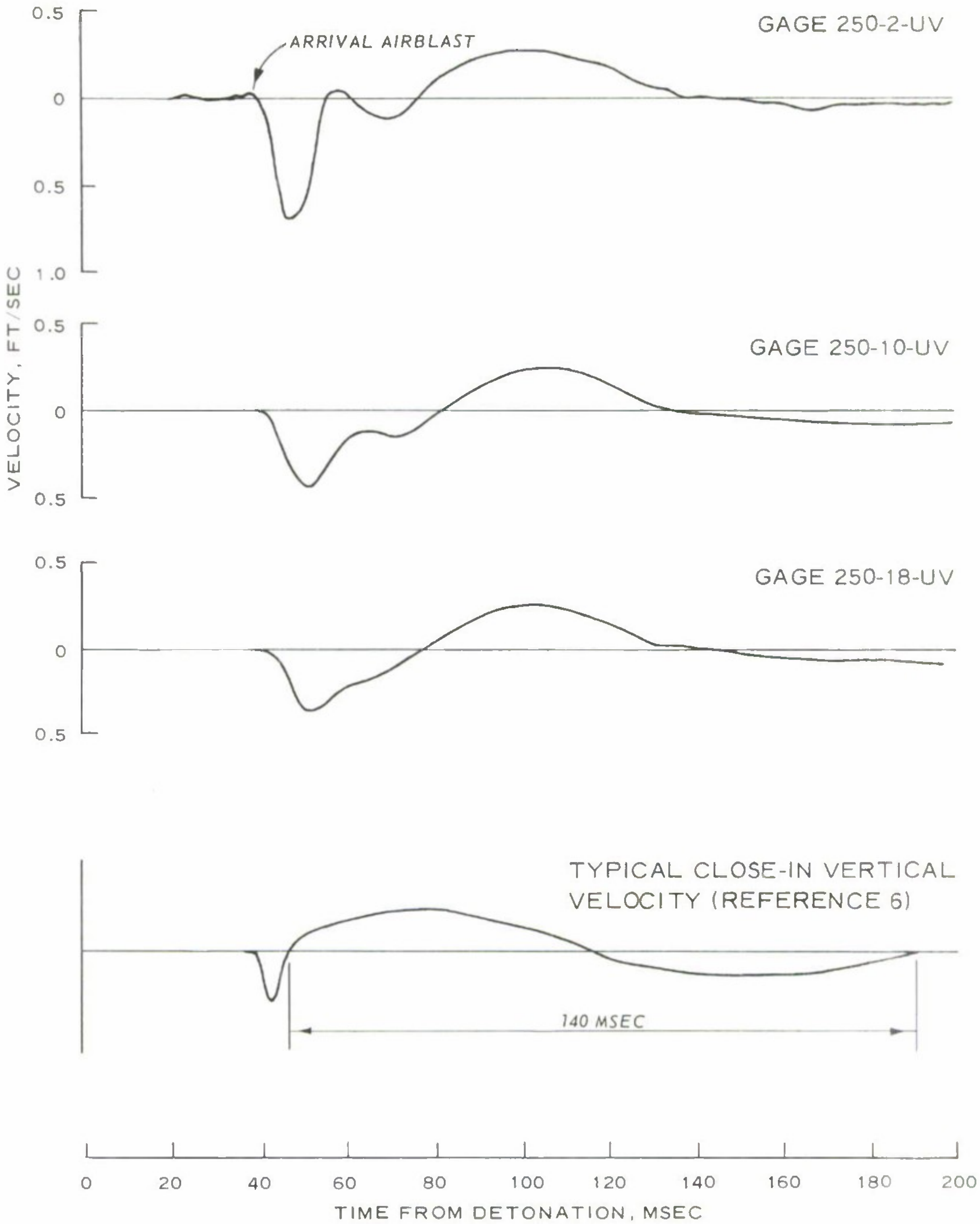


Figure 3.6 Vertical velocity histories, 250-foot range.

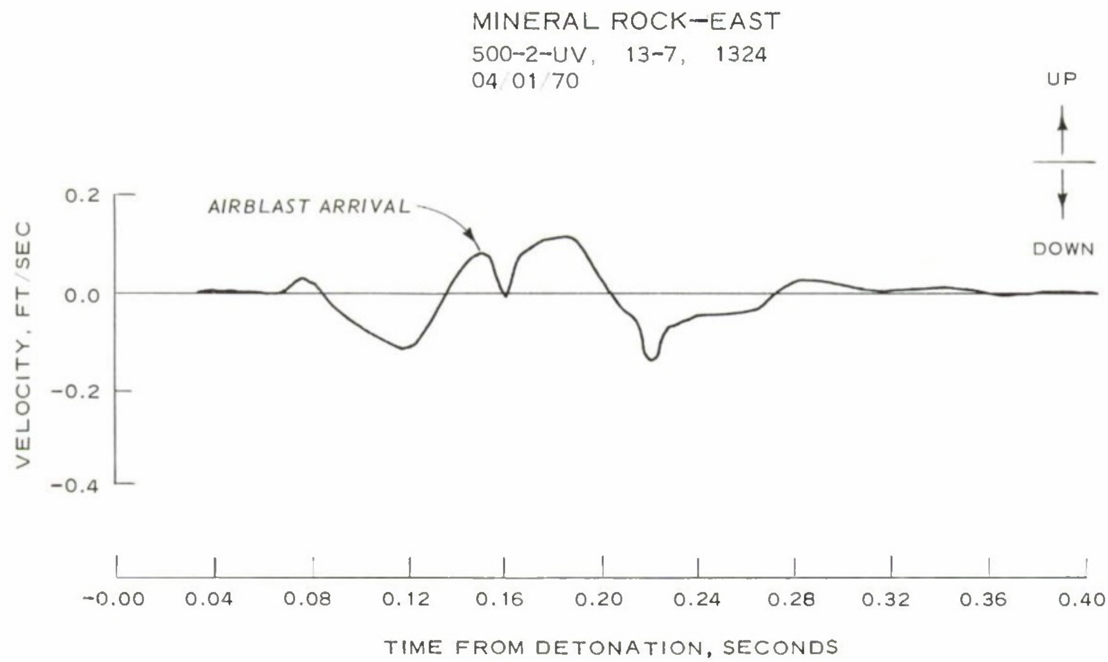


Figure 3.7 Outrunning vertical velocity waveform.

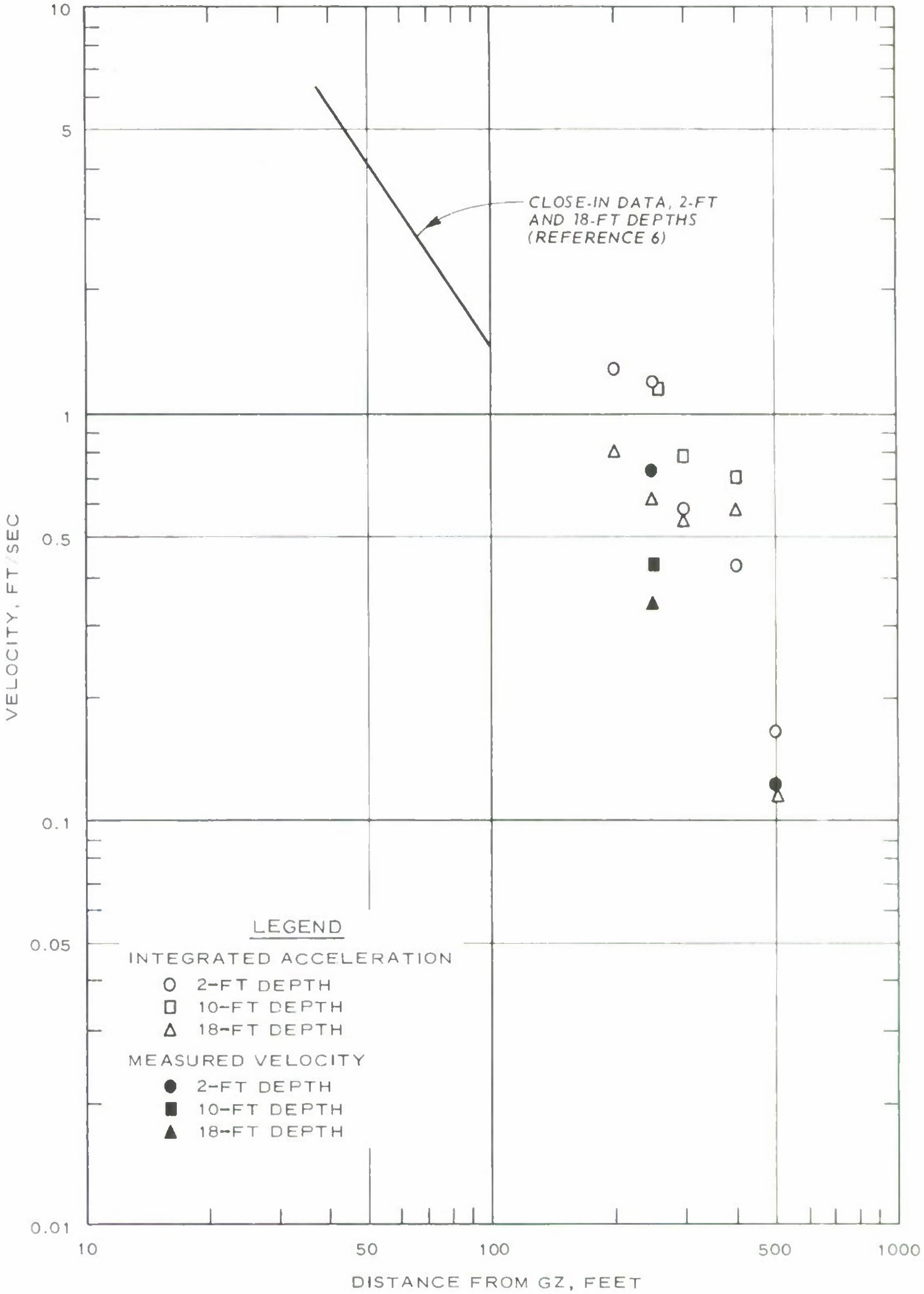


Figure 3.8 Peak downward (airblast-induced) vertical velocity versus distance.

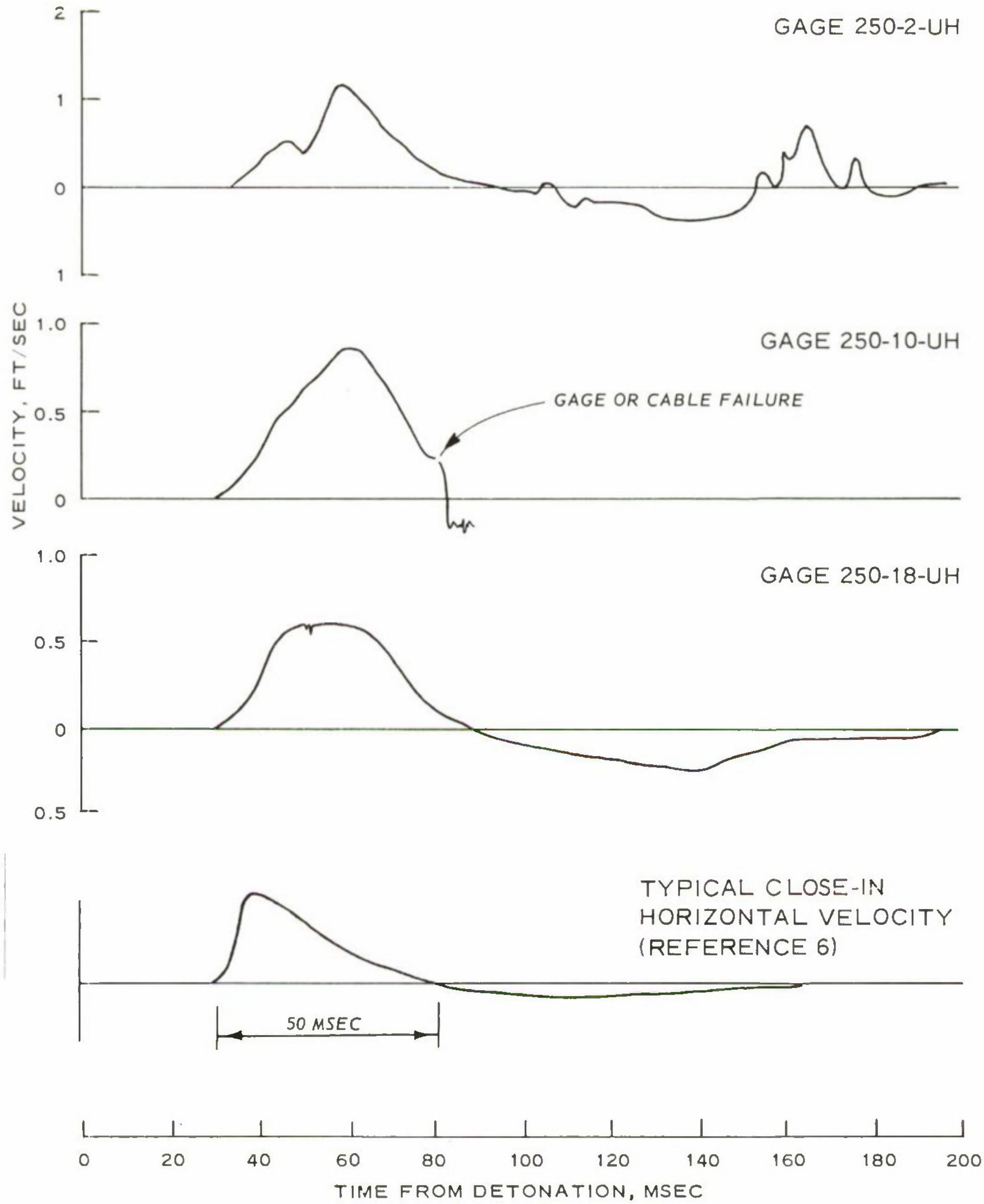


Figure 3.9 Horizontal velocity histories, 250-foot range.

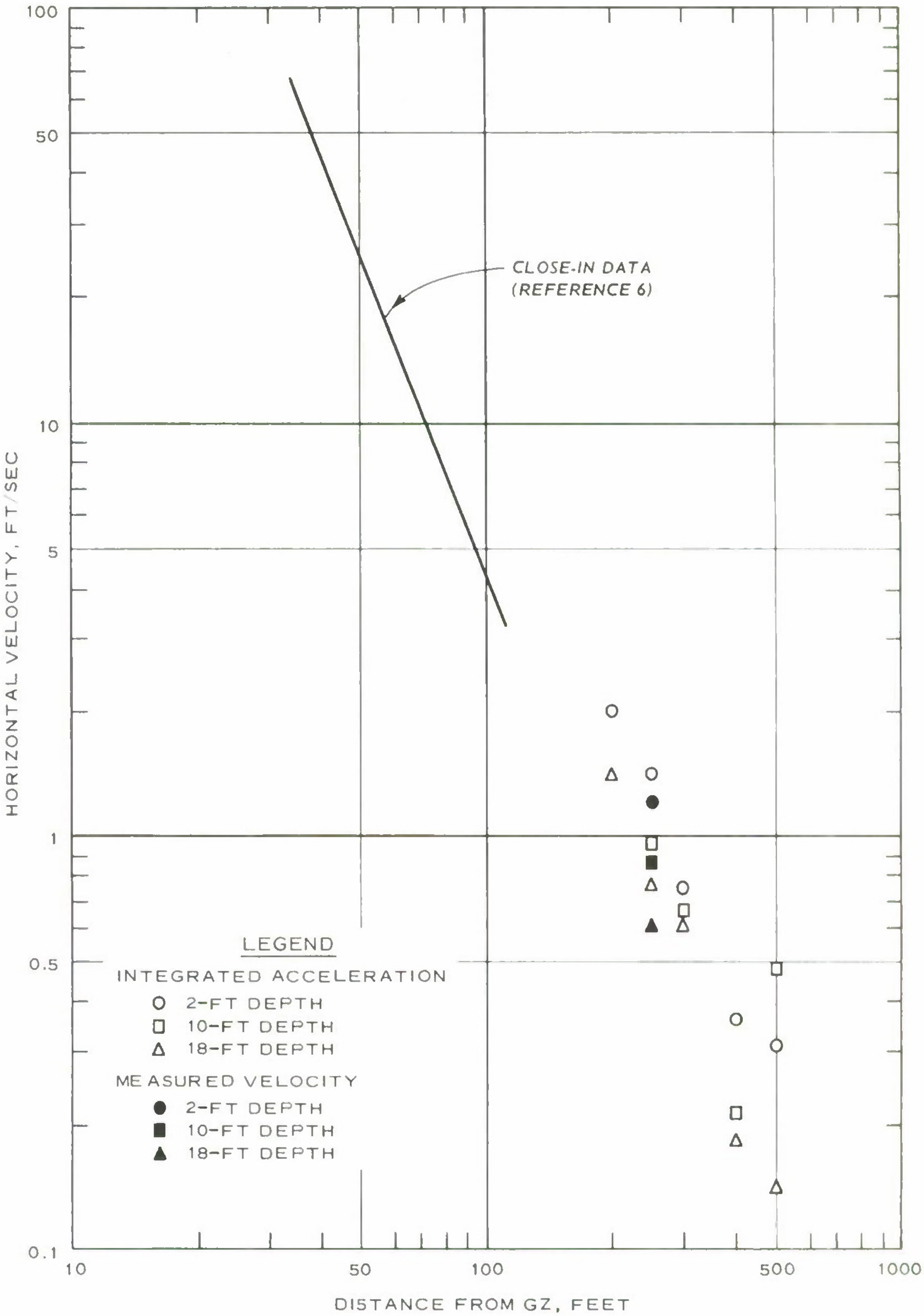


Figure 3.10 Peak horizontal particle velocity versus distance.

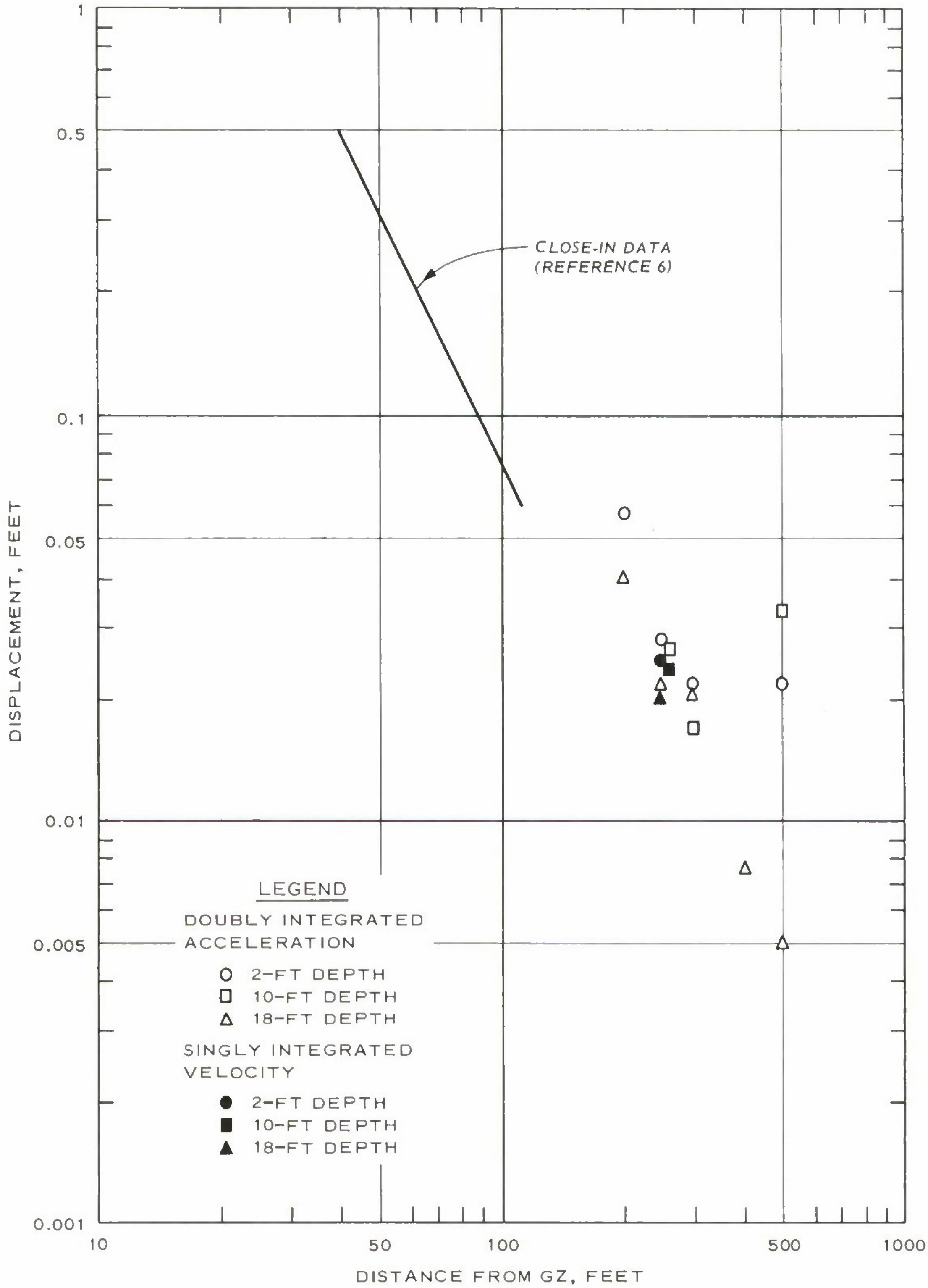


Figure 3.11 Peak horizontal displacement versus distance.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 INSTRUMENT PERFORMANCE

All 36 gages installed for this project were operable at shot time, indicating successful installation insofar as gage or cable damage was concerned. All channels calibrated properly, and recording systems operated correctly as programmed. Two gages (one accelerometer and one velocity gage) produced no readable output and are considered to have failed at shock arrival. The remaining 27 accelerometers were all subjected to a strong electrical noise signal at 20 msec after the detonation. This time was noted to correspond to shock arrival at the nearest approach to GZ of the cable line, and the noise was attributed to shock effects on the cable itself, even though considerable cable protection precautions had been taken. The seven operable velocity gages were not affected.

With the exception of the pressure-induced cable noise, the 34 successfully recorded gages showed good response. The relatively low-frequency response of the velocity gage-System D amplifier system caused some problems in comparing vertical data with acceleration integrals.

Gage and recording system set ranges were sufficiently accurate that good signal amplitude was obtained on all channels. All signals were well above normal system background noise, yet no channels were driven out of band.

4.2 MOTION MEASUREMENTS

Peak downward airblast-induced vertical accelerations were found to attenuate sharply with both distance and depth from the maximum value of 32 g's at the 200-foot range and 2-foot depth. Vertical airblast-induced accelerations were noted to correlate well with overpressure, averaging about 0.2 g/psi for the 2-foot depth. This ratio is approximately one-fourth that for 100-ton detonations over soil.

Peak horizontal accelerations were also generally associated with passage of airblast and were approximately one-half the vertical peaks at the

2- and 10-foot depths; at the 18-foot depth, horizontal accelerations were about three-fourths the vertical.

Downward airblast-induced vertical velocities attenuated with distance and depth, although attenuation with depth was less regular than for accelerations. This is attributed partially to the noisy accelerograms which did not produce very reliable integrals. No measurable vertical outrunning velocity was noted at the 250-foot range. At the 500-foot range, however, the outrunning pulse had a significant vertical component of both greater magnitude and longer duration than the airblast-induced motion. Horizontal velocities followed much the same pattern as did the vertical, and over the range instrumented were roughly equal to vertical peaks. Horizontal velocities generally showed considerable outrunning motion, with the airblast-induced pulse superposed on a long-duration outward pulse. Relative velocity contributions of the two pulses were quantitatively indeterminate, although due to its duration, the outrunning (directly induced) motion would be the primary source of displacements.

Vertical displacement measurements of a high confidence level were limited to the 250-foot range. Very little attenuation with depth was noted, with displacements ranging from 0.0075 foot at the 2-foot depth to 0.0060 foot at the 18-foot depth. Horizontal displacements were successfully computed from both velocity and acceleration data. At the 250-foot range, they were three to four times as large as the vertical displacements.

4.3 RECOMMENDATIONS

Recommendations for future work fall into two categories: (1) changes or improvements in basic experiment design, and (2) changes in operational procedure.

Under the first of these, it is recommended that a larger percentage of channel space on future tests be devoted to velocity gages. This provides generally more reliable displacement data and, except where acceleration data itself is of vital importance, should be the primary instrumentation. Where accelerations are required, velocity gages provide excellent back-up data.

Additionally, instrument locations should be spread over as wide a

range of distance and depth as practical in order to adequately define attenuation patterns.

Under the second category, the cable protection methods used for Mineral Rock were apparently inadequate. Since pressure effects had not been noticed on prior tests, protection from ejecta missiles was uppermost in mind, and cables were adequately protected from this hazard. Pressure protection for future tests could be offered by more judicious (though more expensive) cable routing and by protection by encasing in pressure-proof material such as conduit.

APPENDIX A

MOTION-TIME HISTORIES

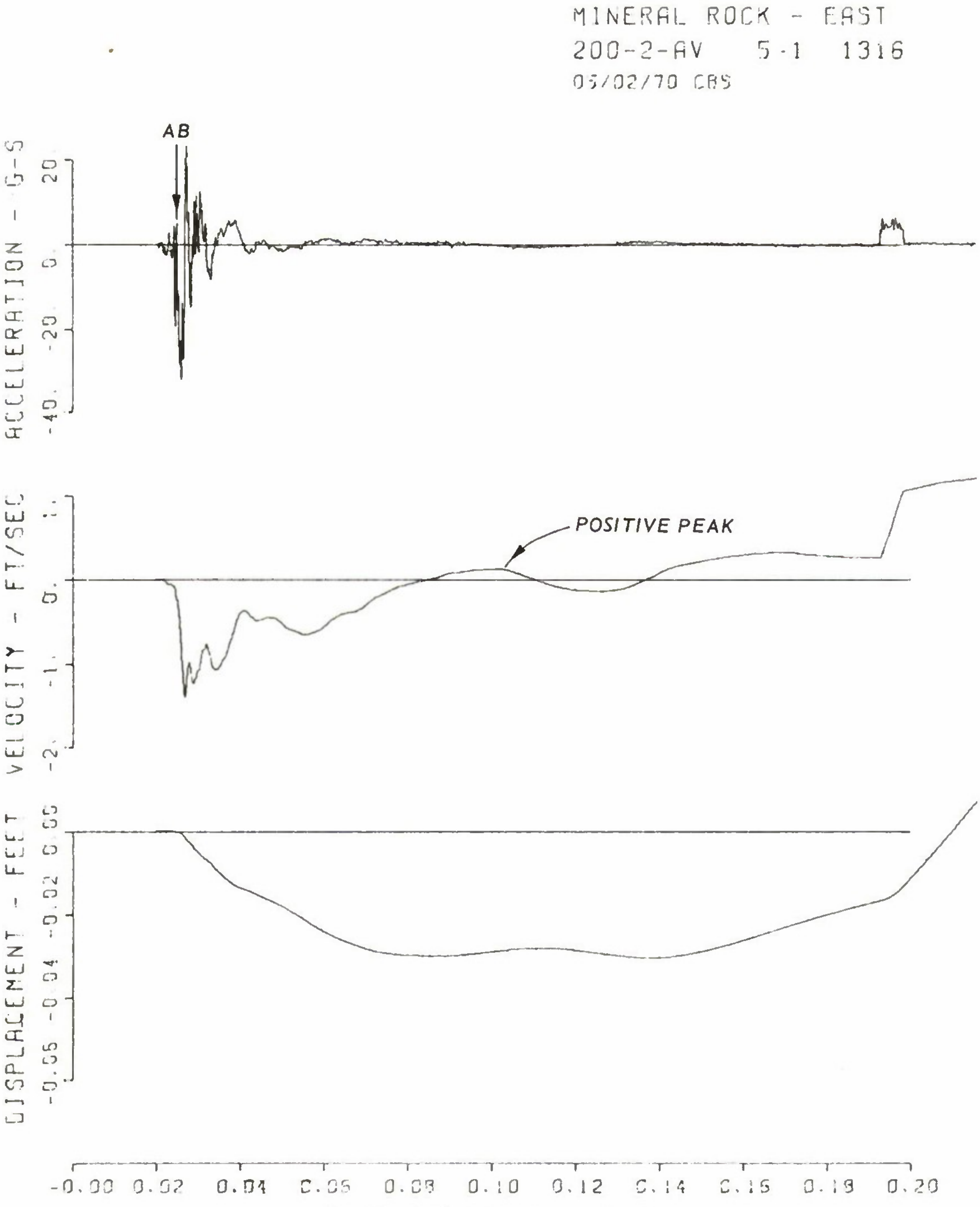


Figure A.1 Gage 200-2-AV.

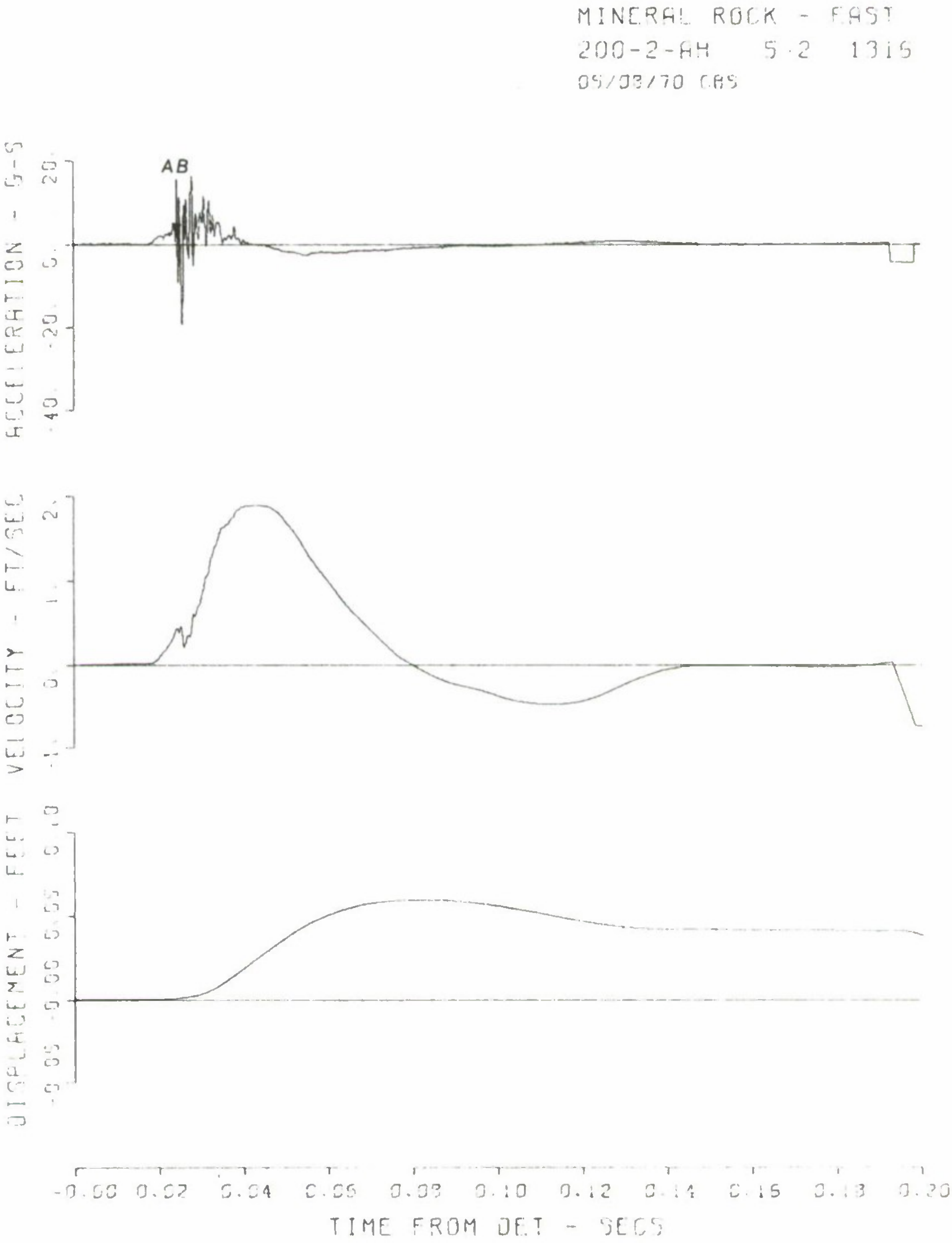


Figure A.2 Gage 200-2-AH.

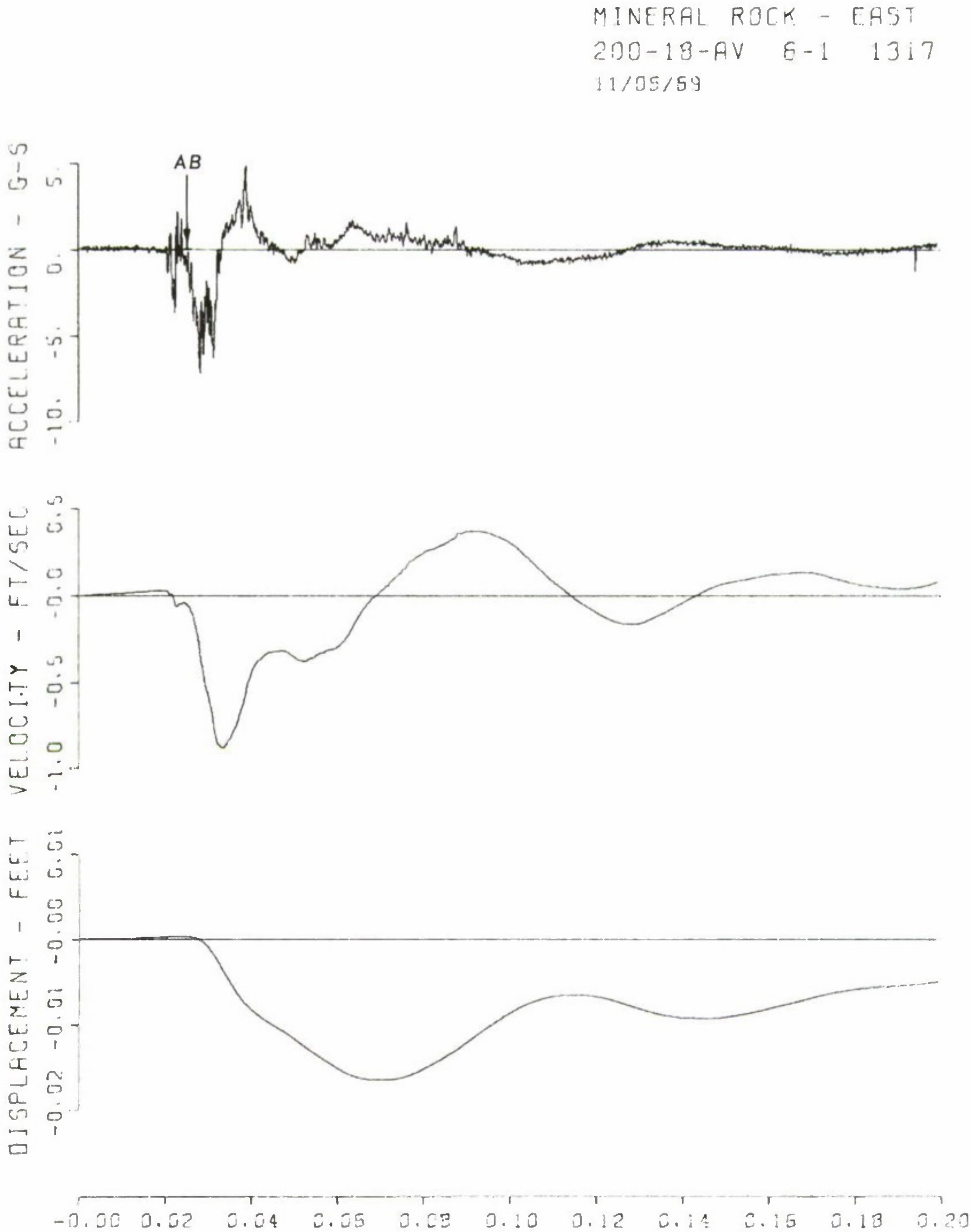


Figure A.3 Gage 200-18-AV.

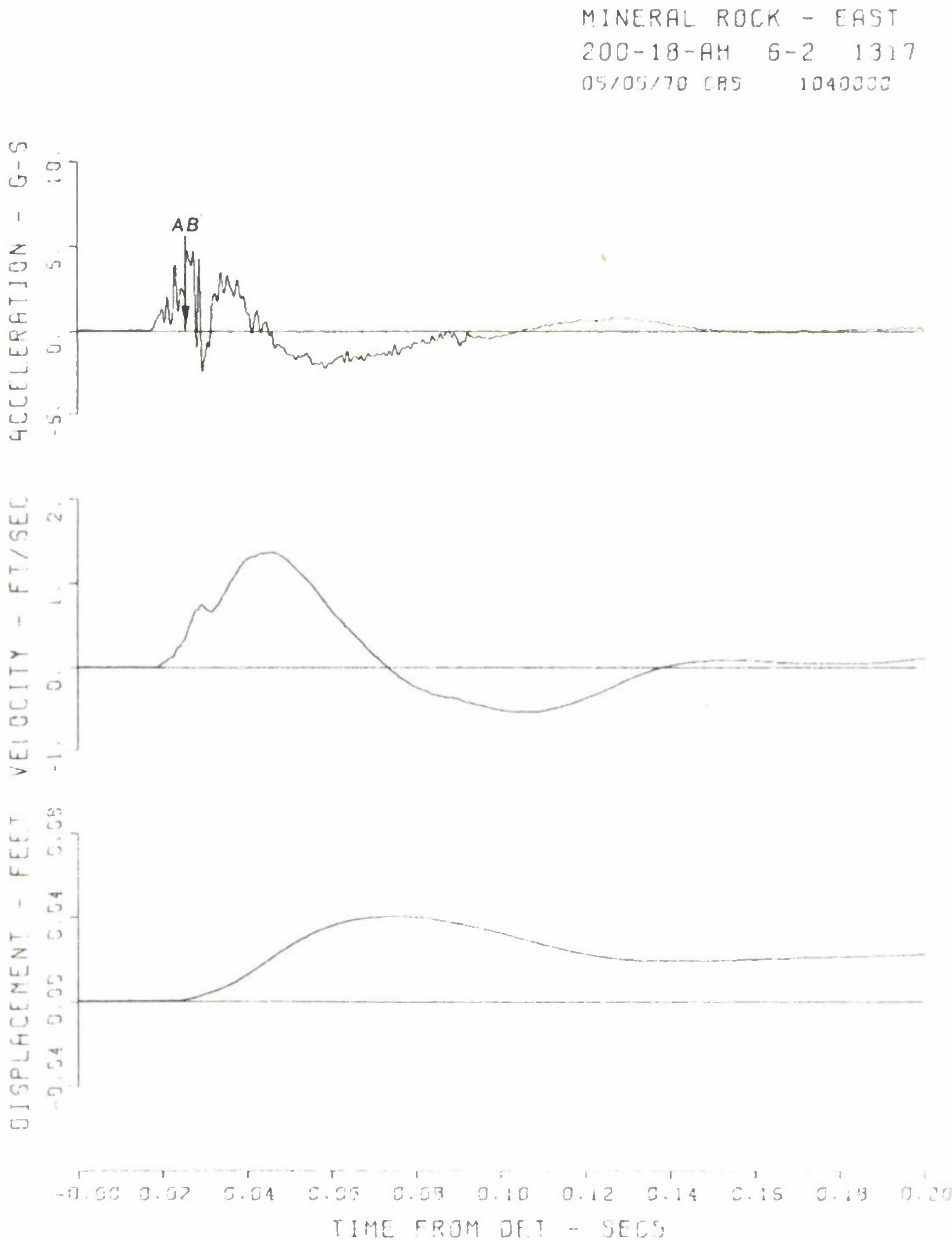


Figure A.4 Gage 200-18-AH.

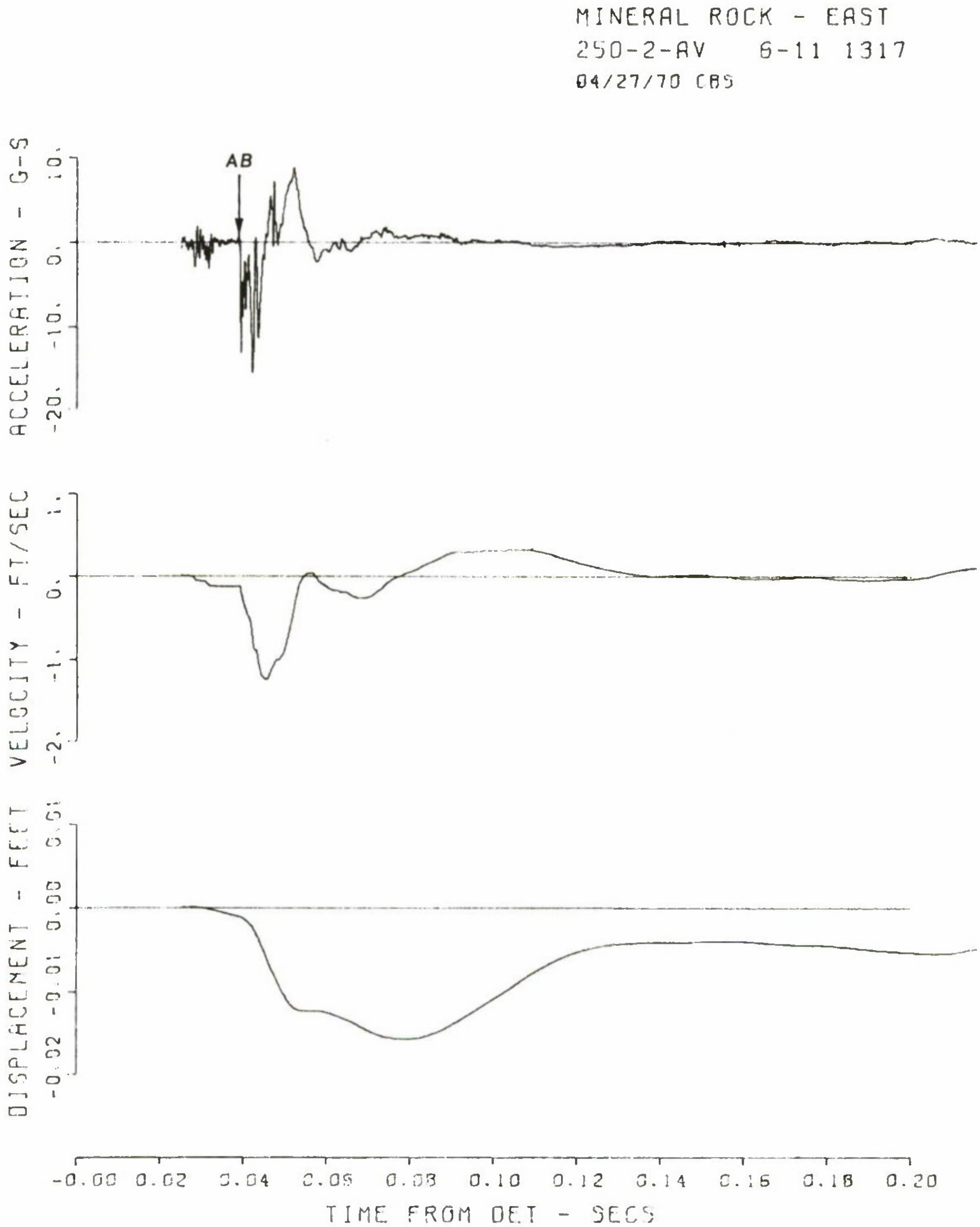


Figure A.5 Gage 250-2-AV.

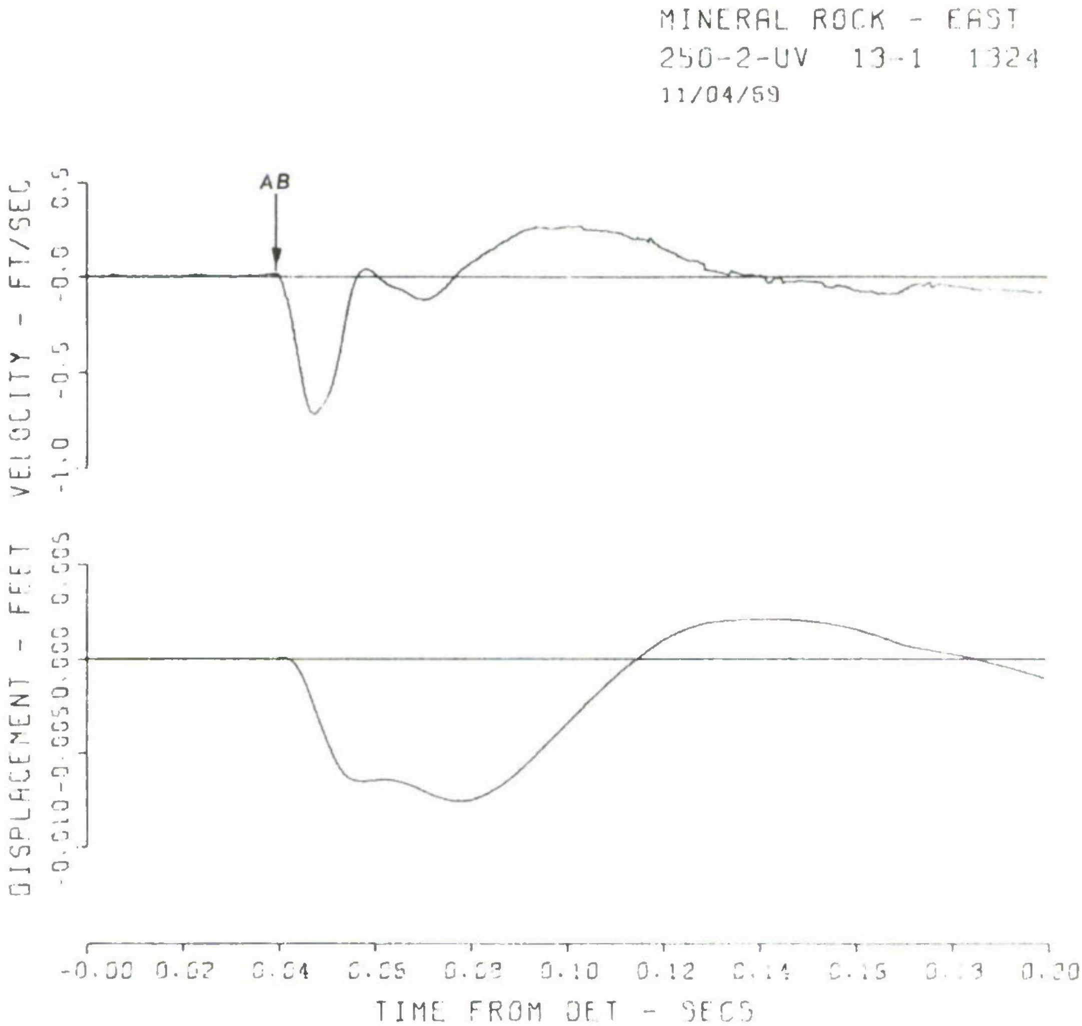


Figure A.6 Gage 250-2-UV.

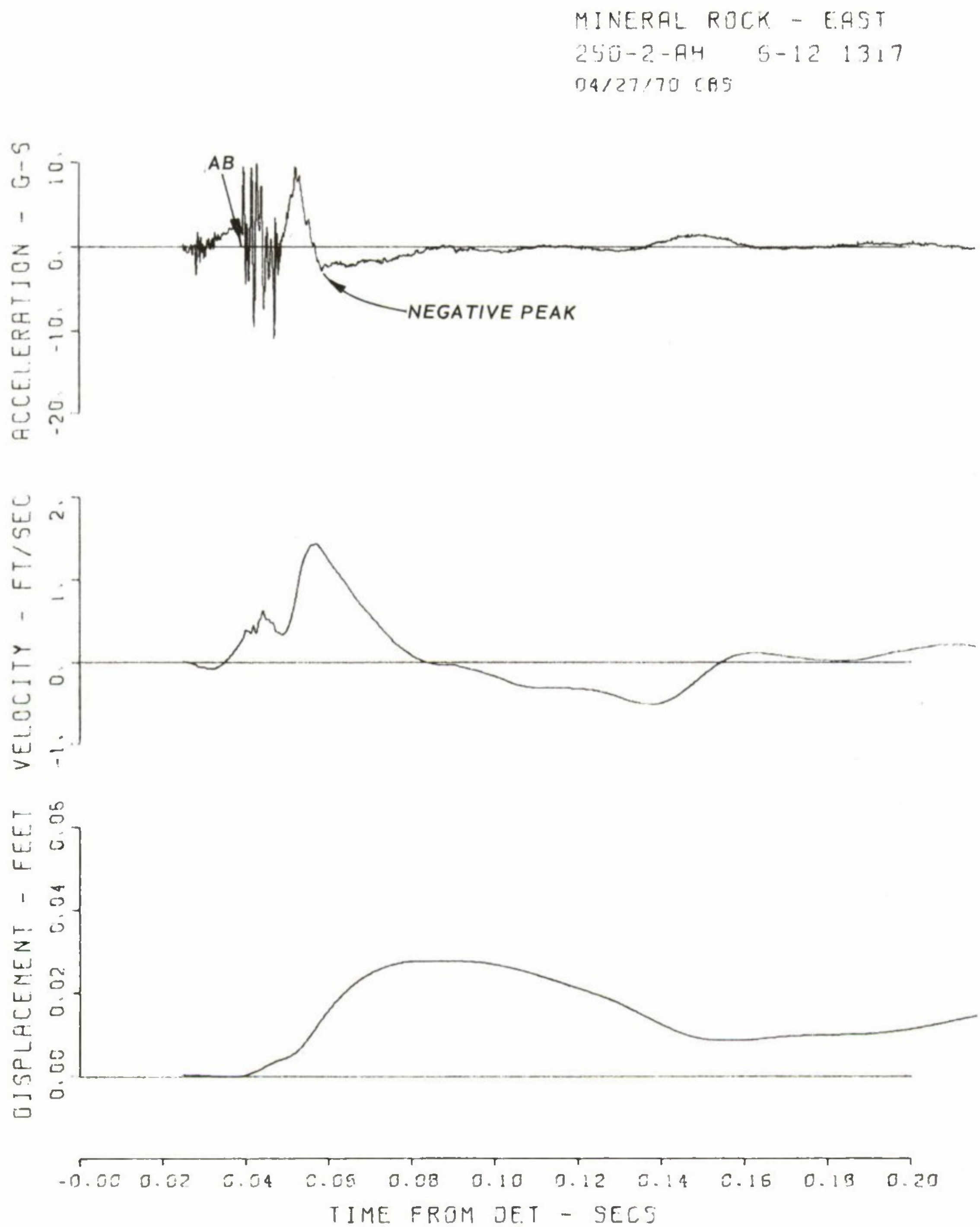


Figure A.7 Gage 250-2-AH.

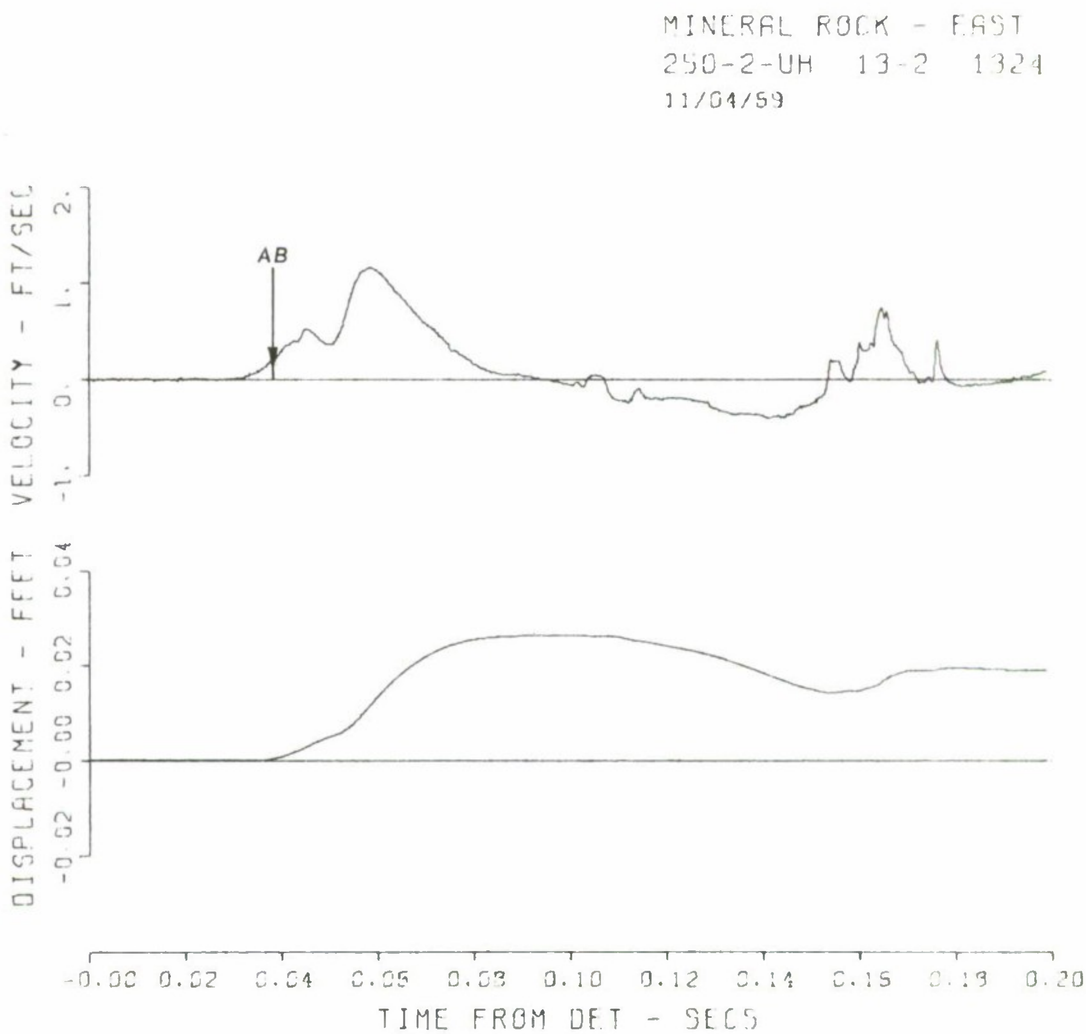


Figure A.8 Gage 250-2-UH.

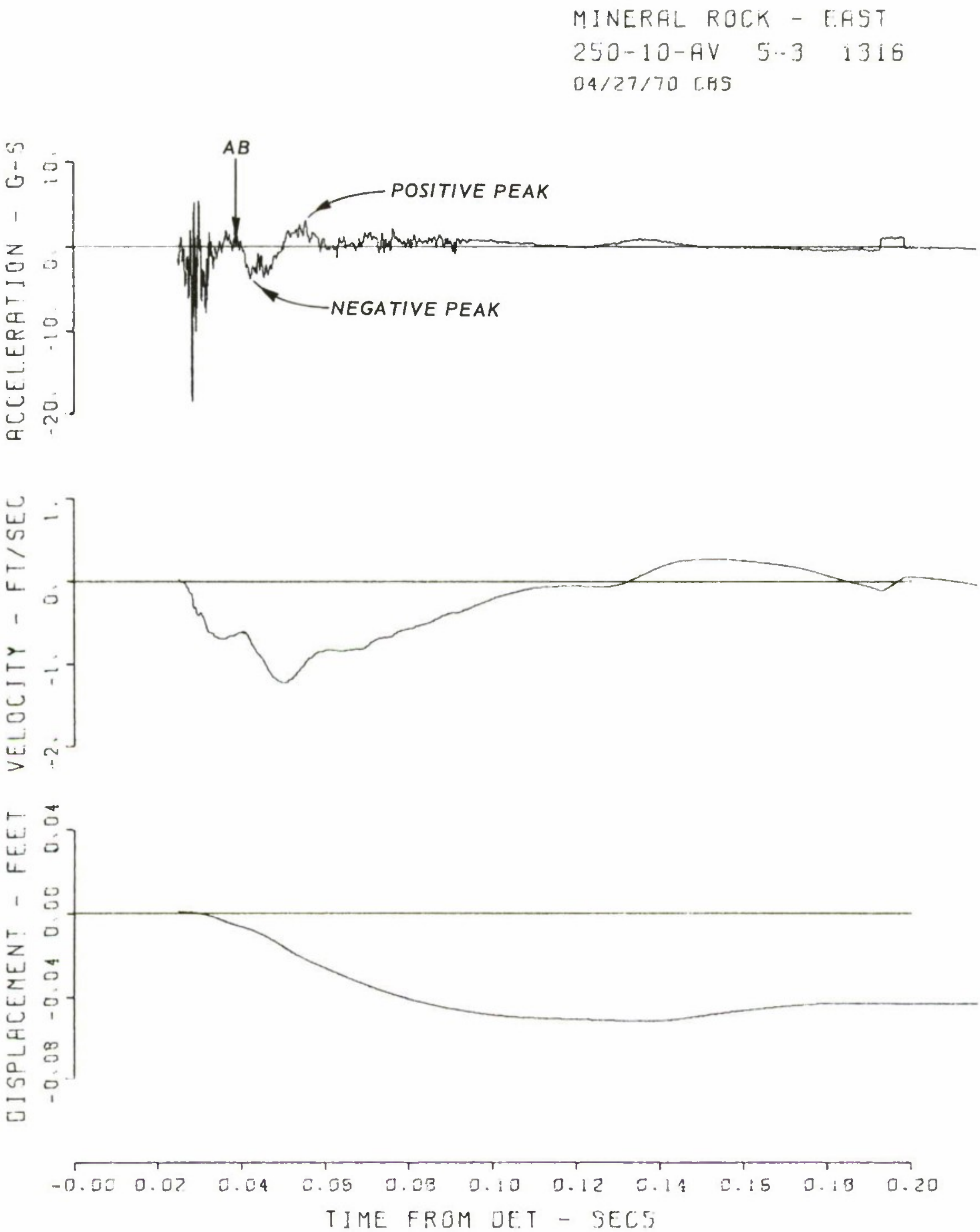


Figure A.9 Gage 250-10-AV.

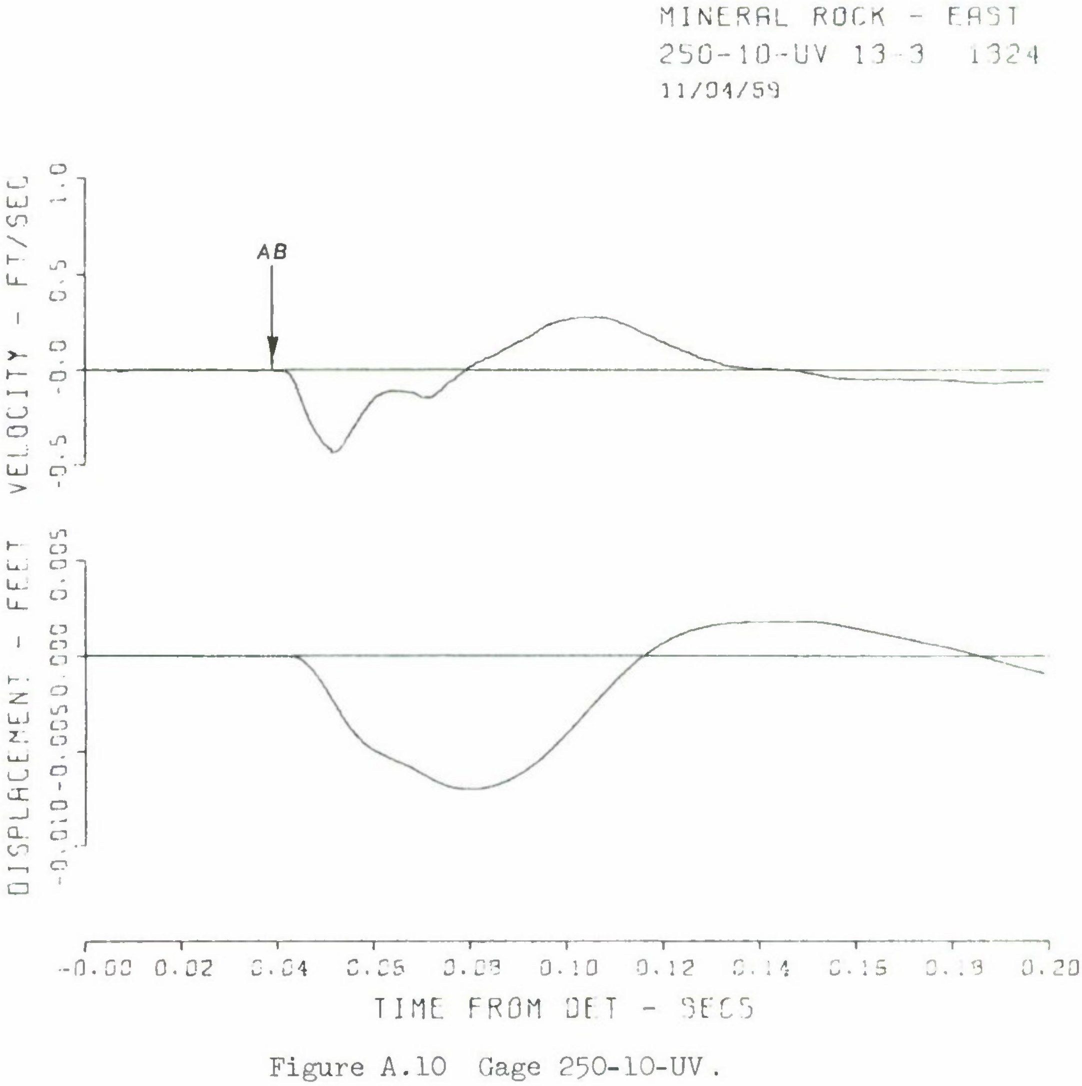


Figure A.10 Gage 250-10-UV.

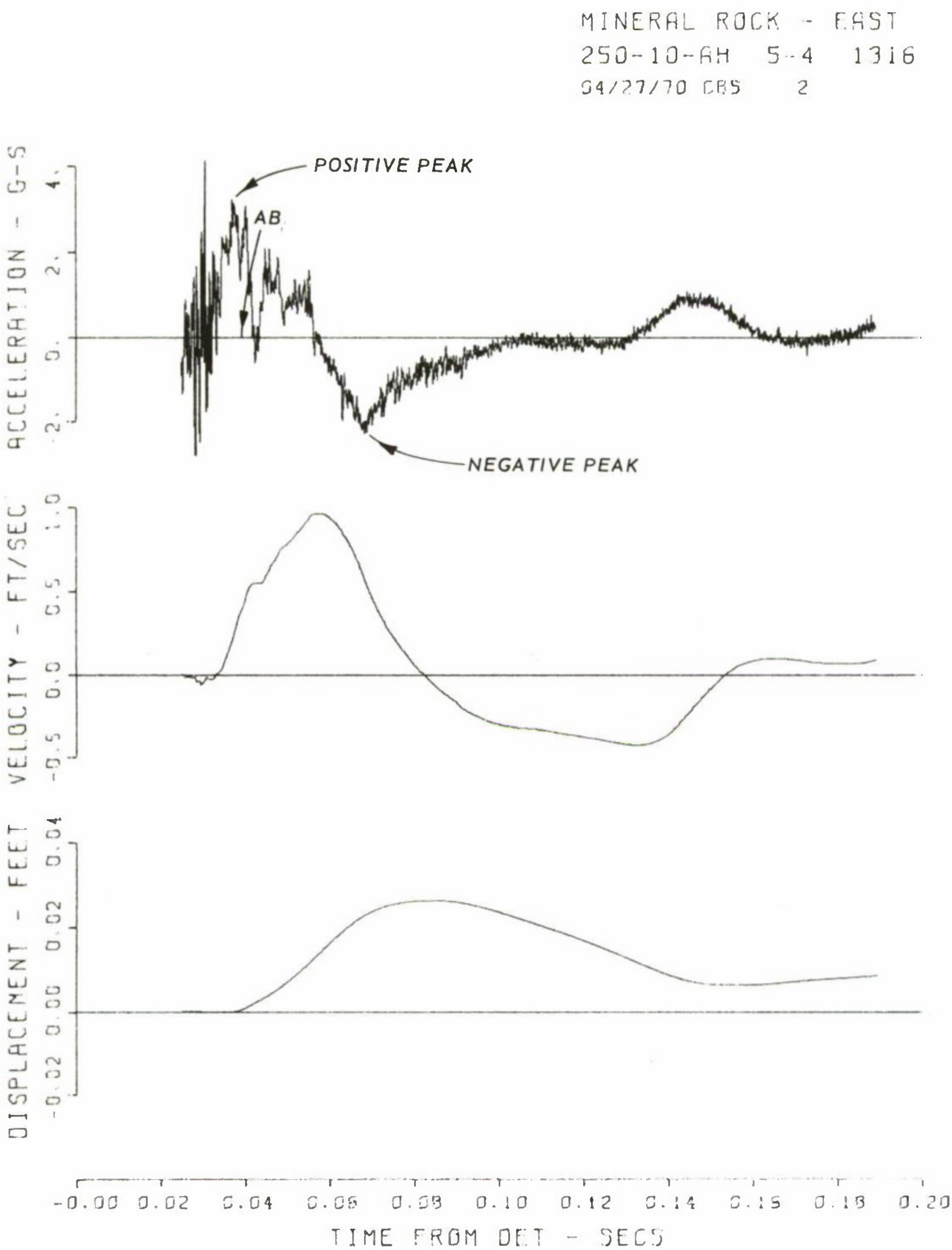


Figure A.11 Gage 250-10-AH.

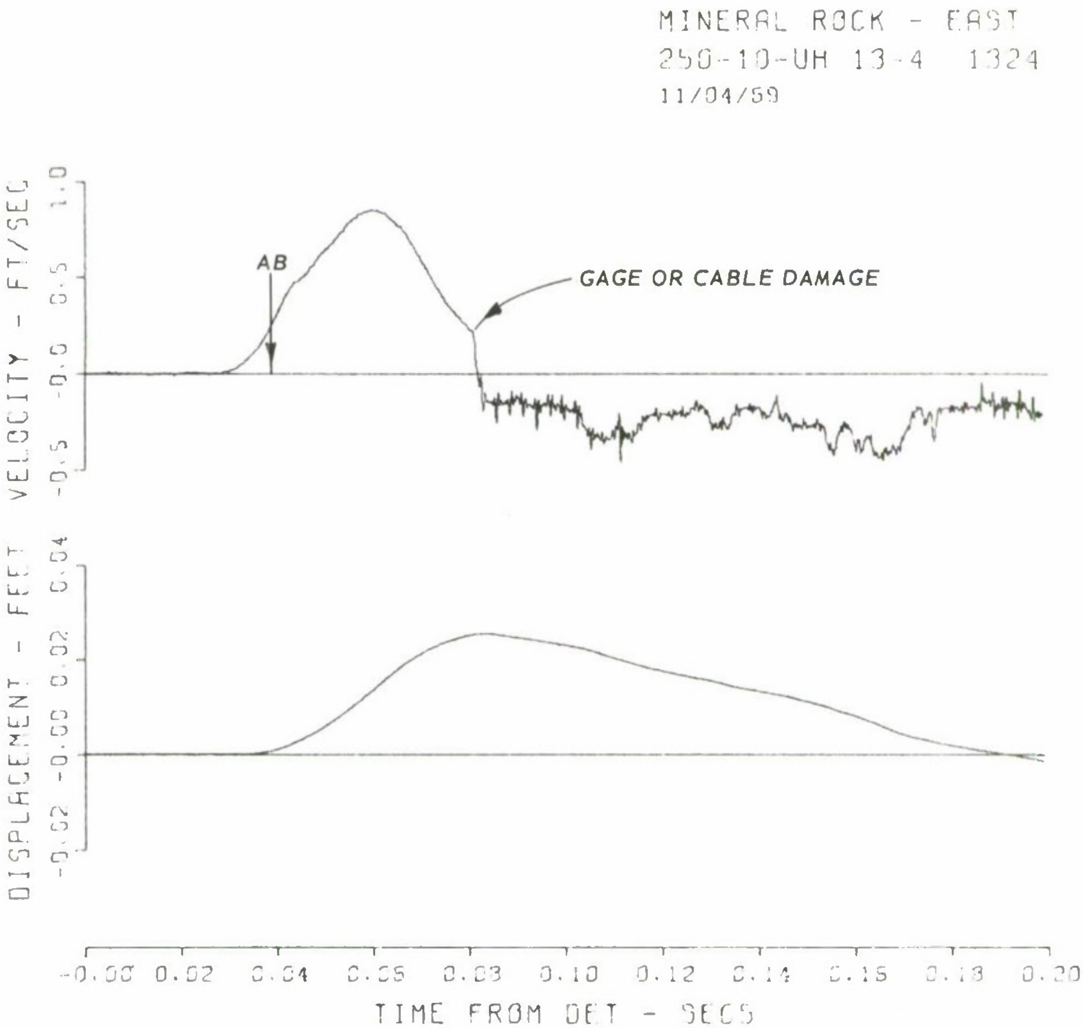


Figure A.12 Gage 250-10-UH.

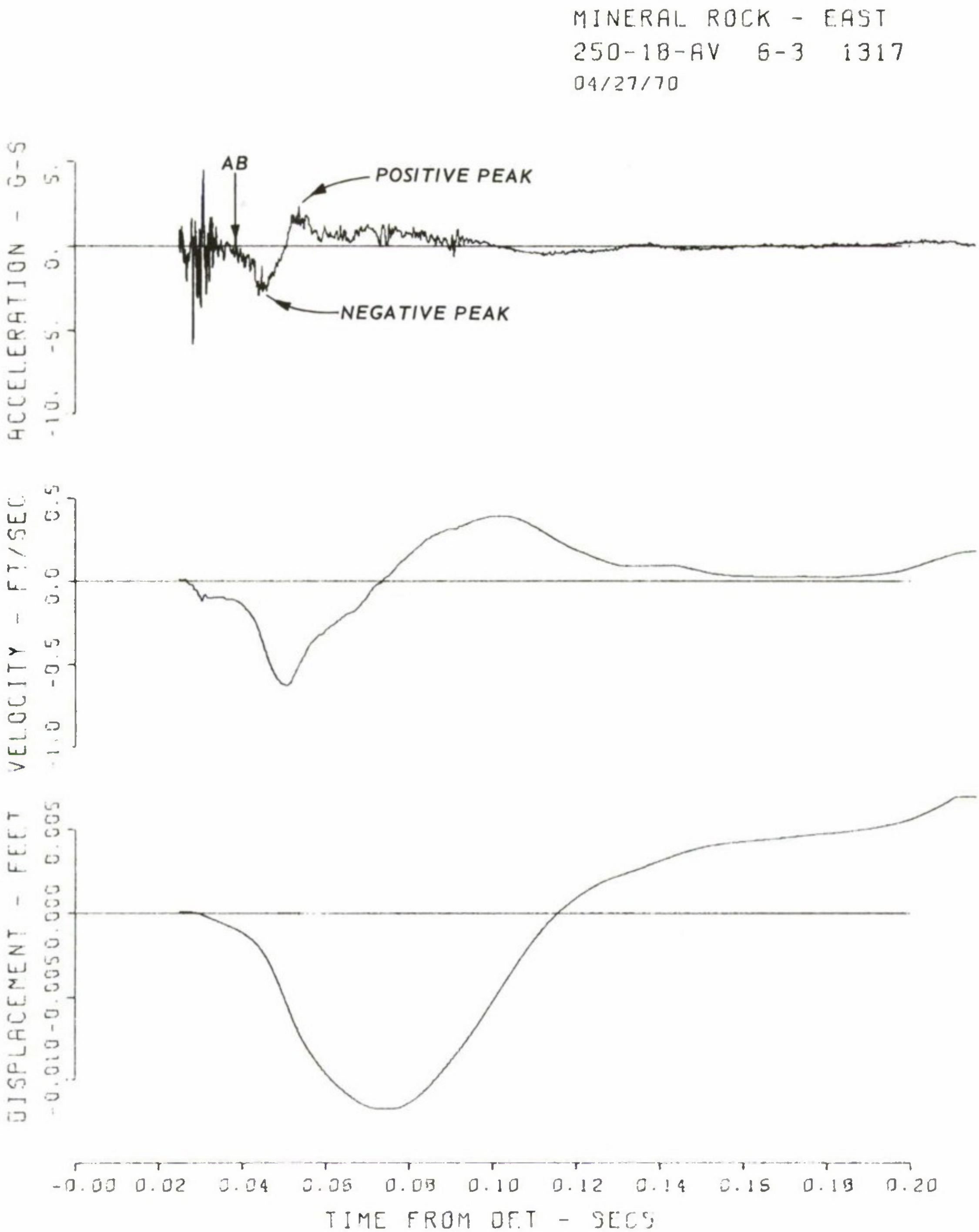


Figure A.13 Gage 250-18-AV.

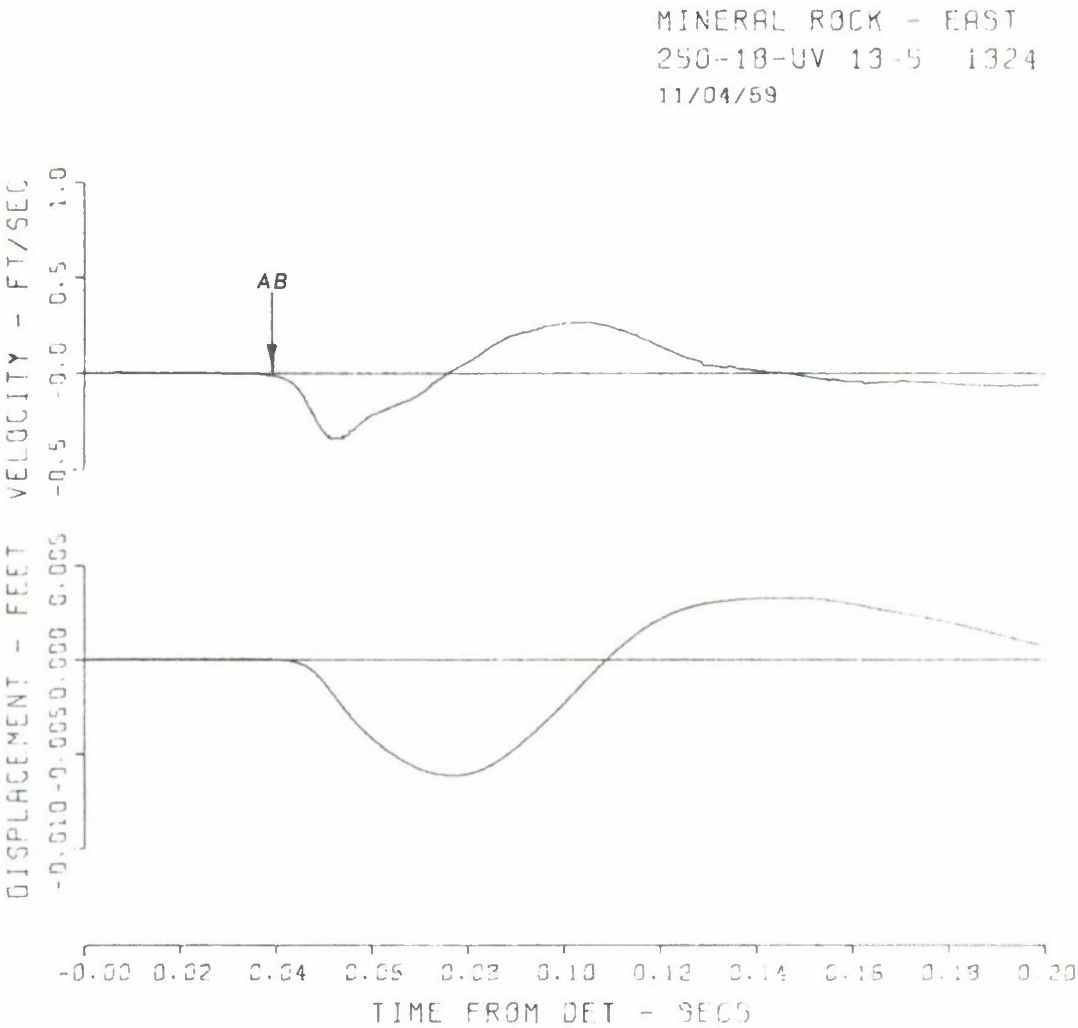


Figure A.14 Gage 250-18-UV.

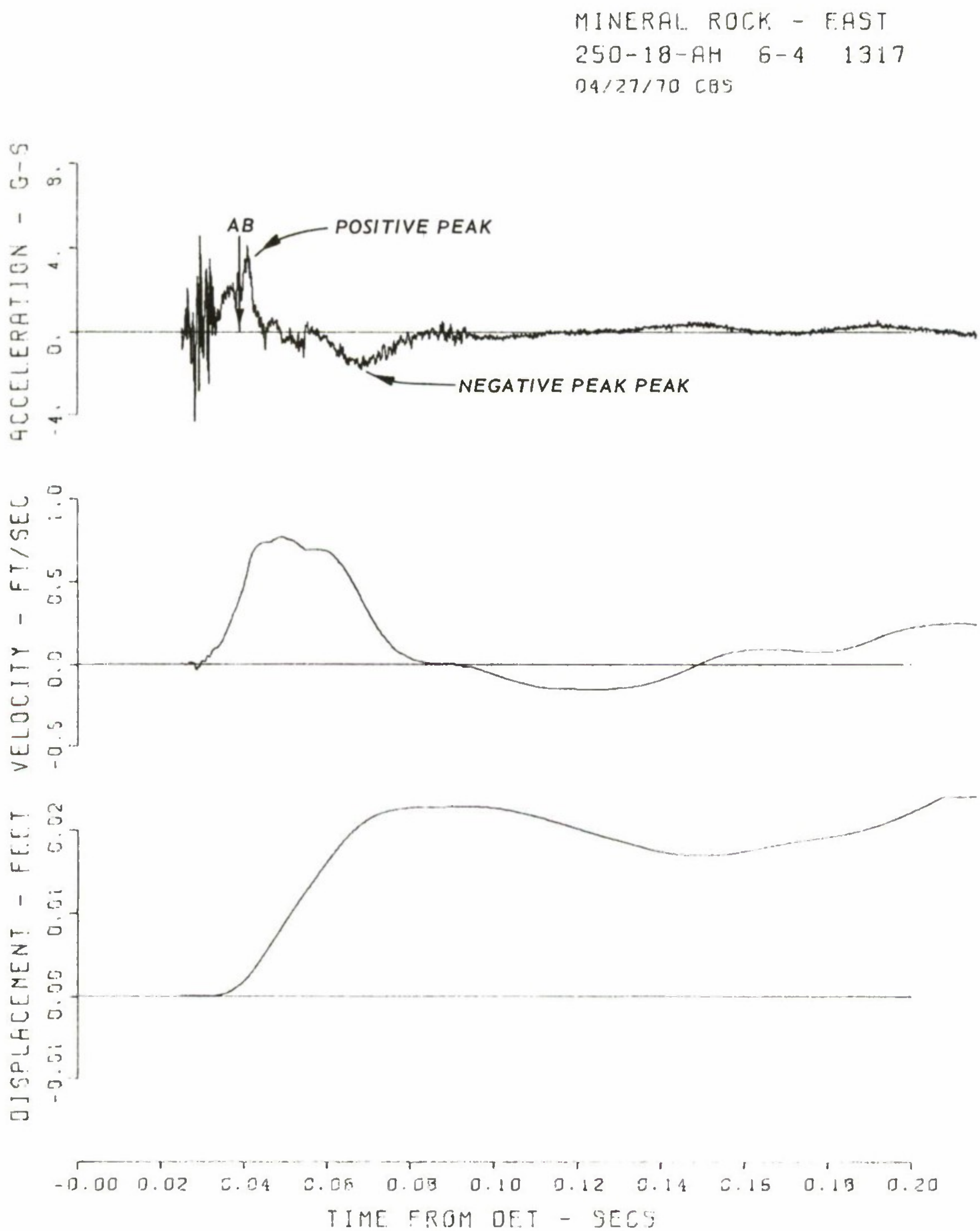


Figure A.15 Gage 250-18-AH.

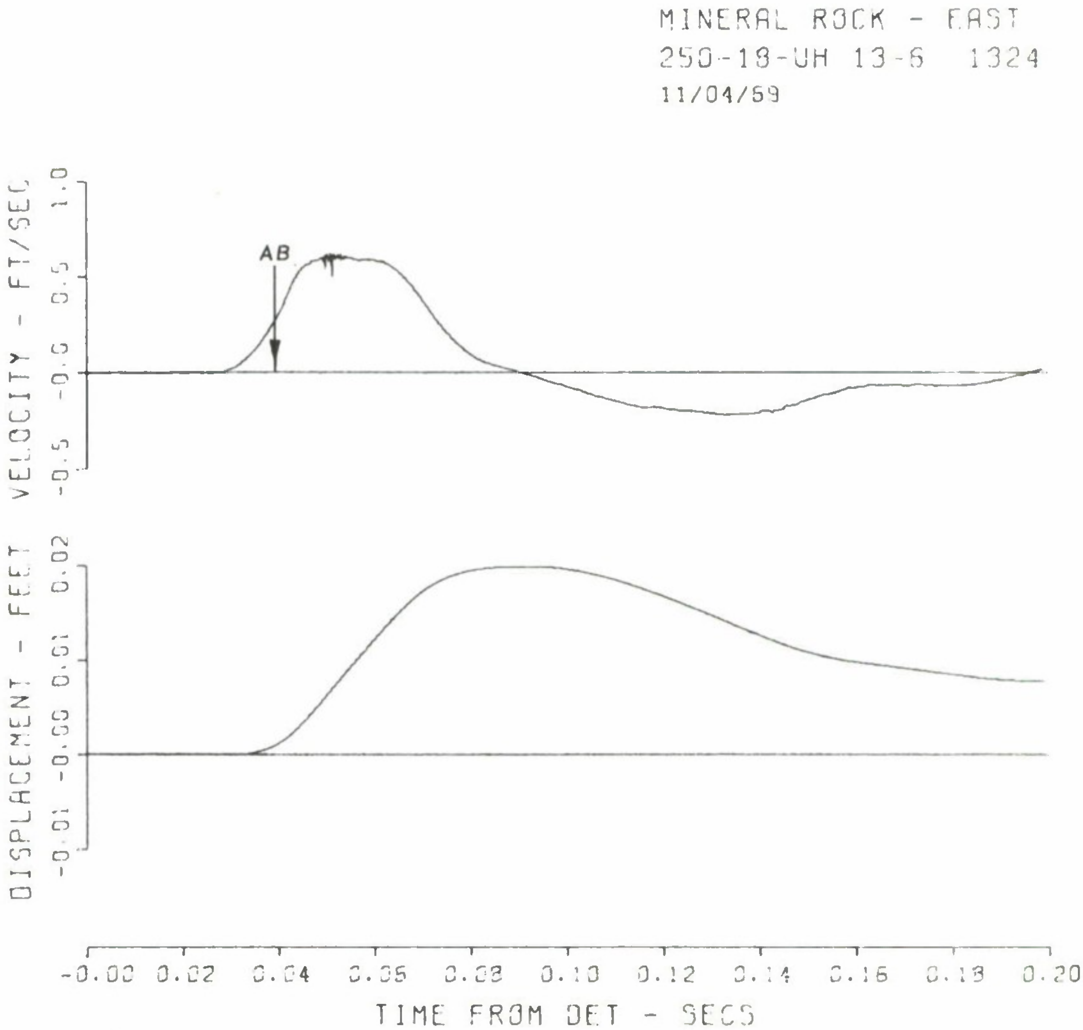


Figure A.16 Gage 250-18-UH.

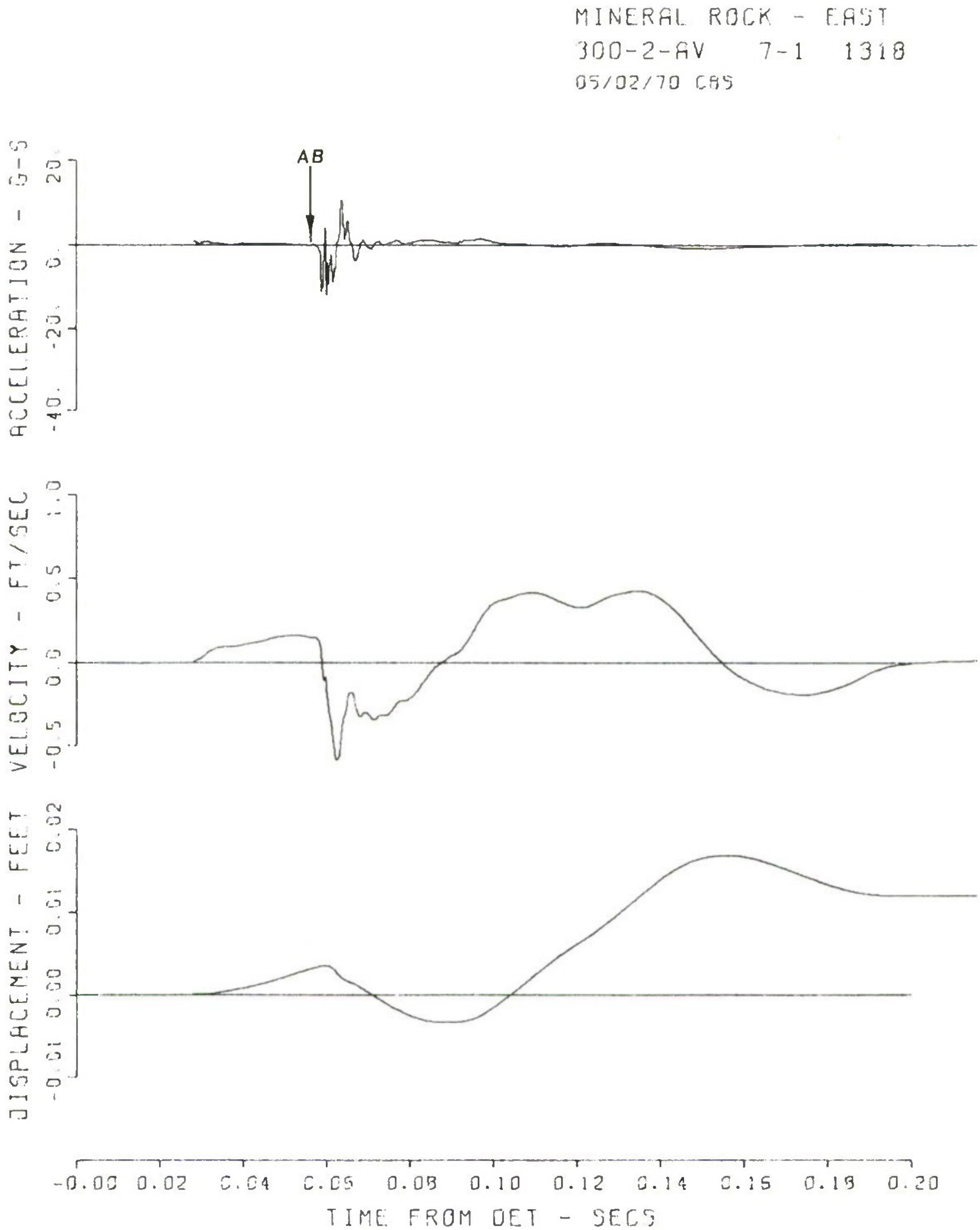


Figure A.17 Gage 300-2-AV.

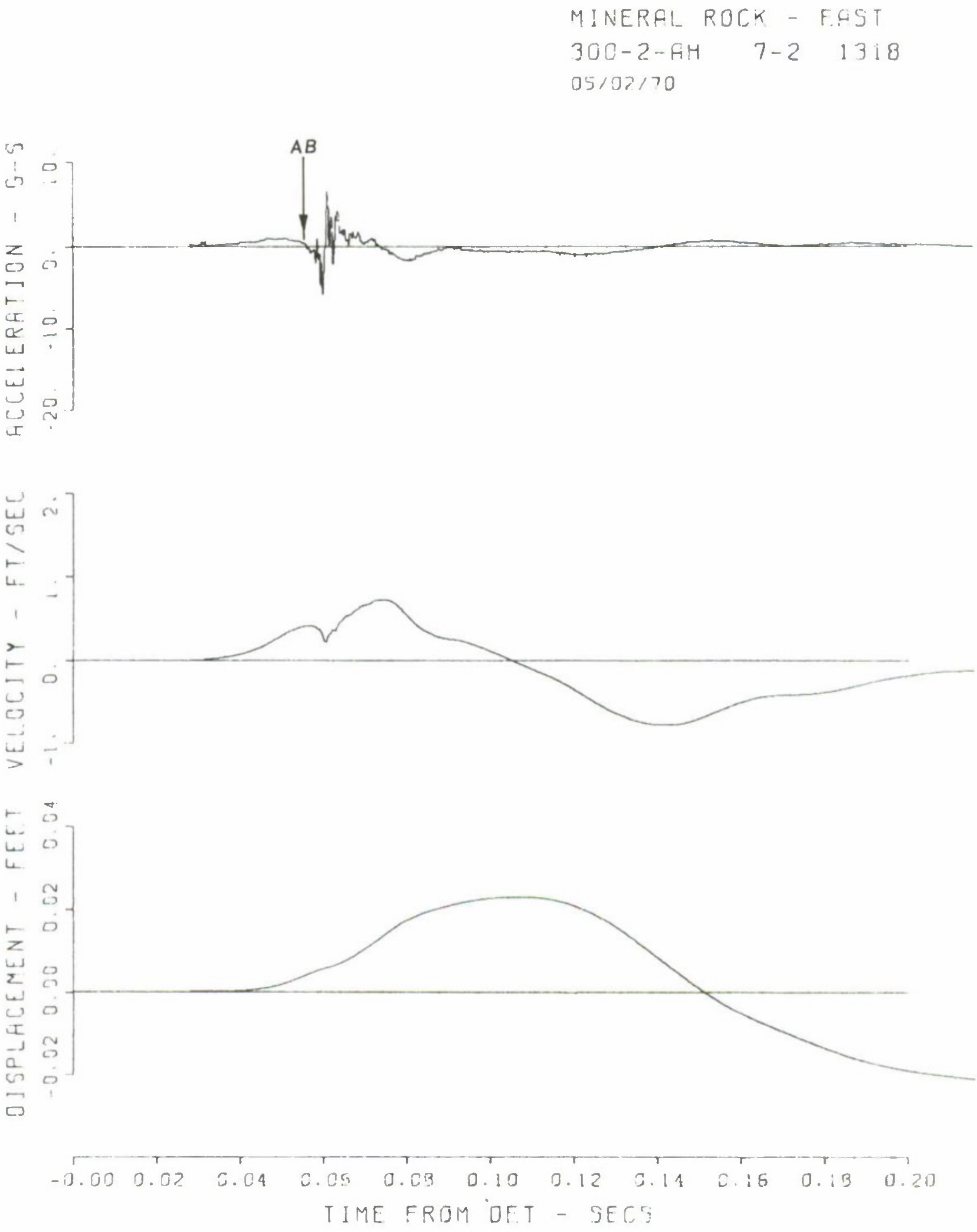


Figure A.18 Gage 300-2-AH.

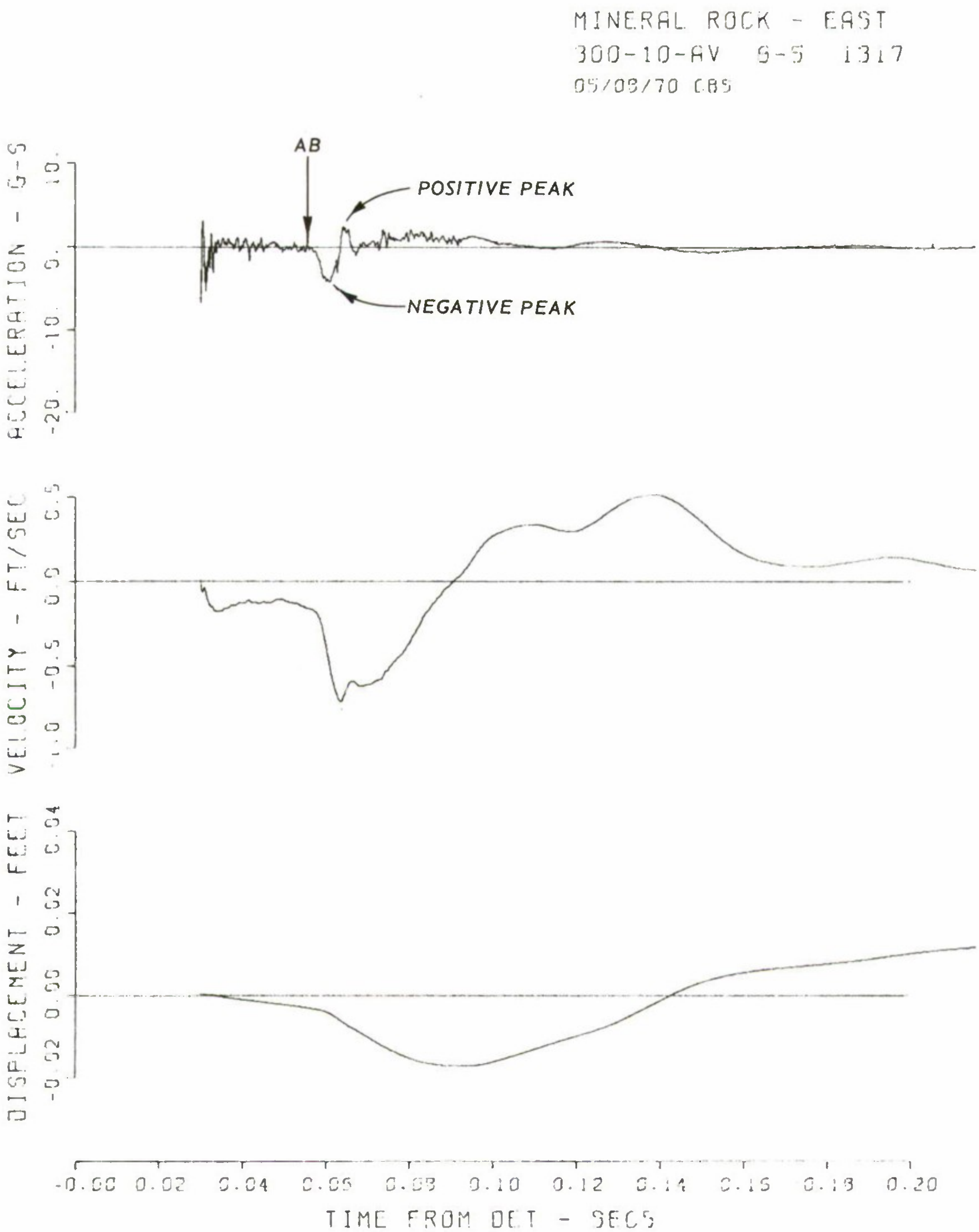


Figure A.19 Gage 300-10-AV.

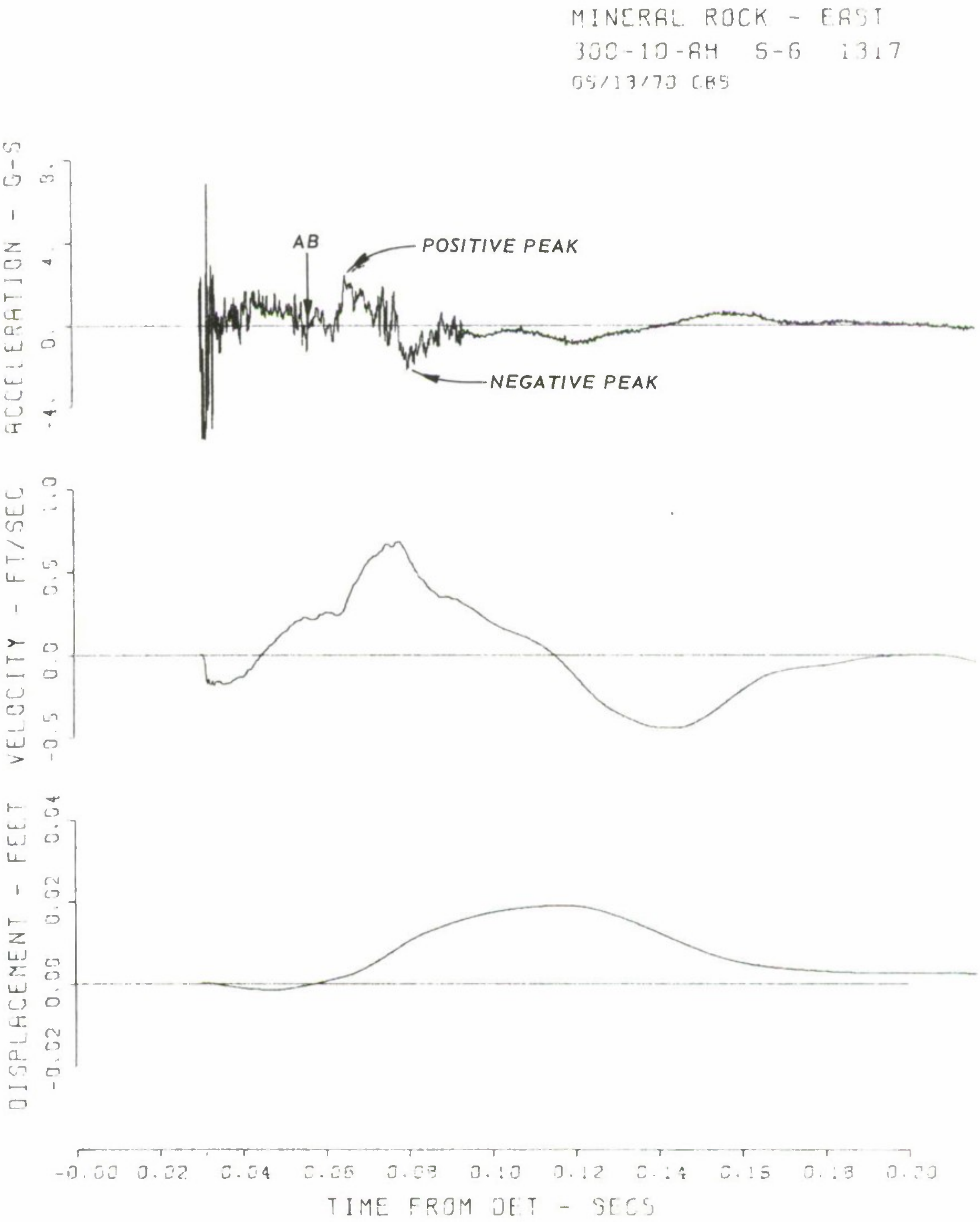


Figure A.20 Gage 300-10-AH.

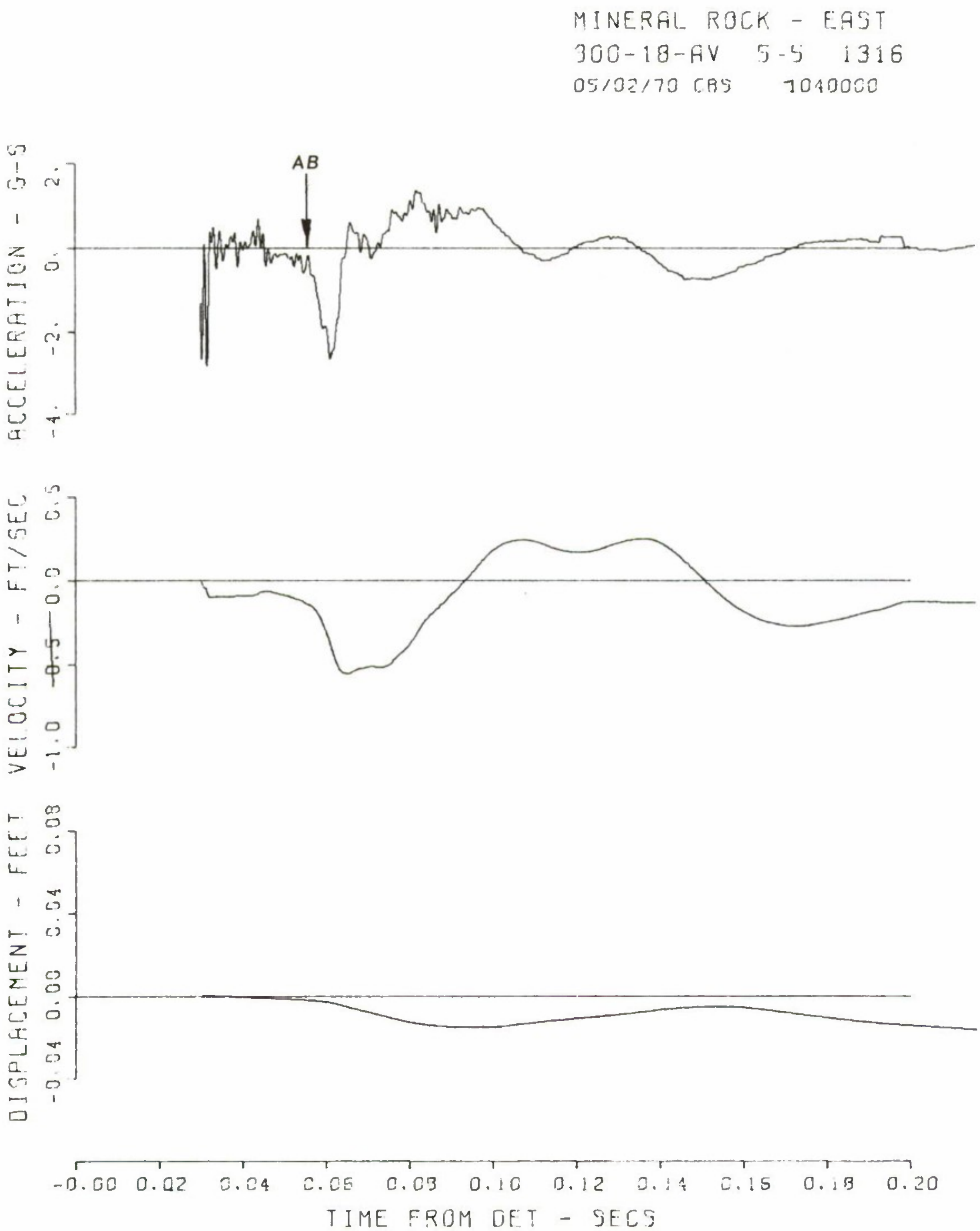


Figure A.21 Gage 300-18-AV.

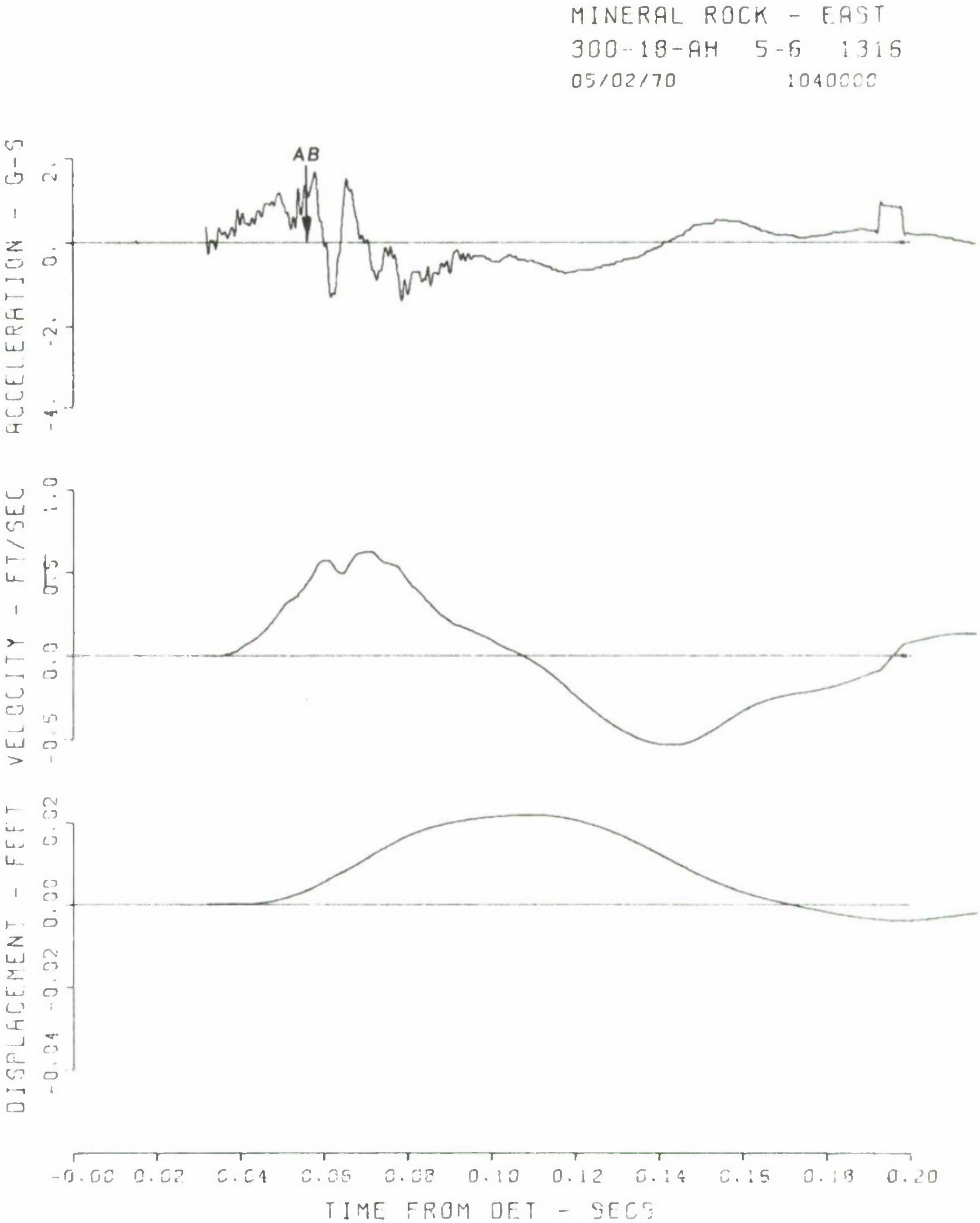


Figure A.22 Gage 300-18-AH.

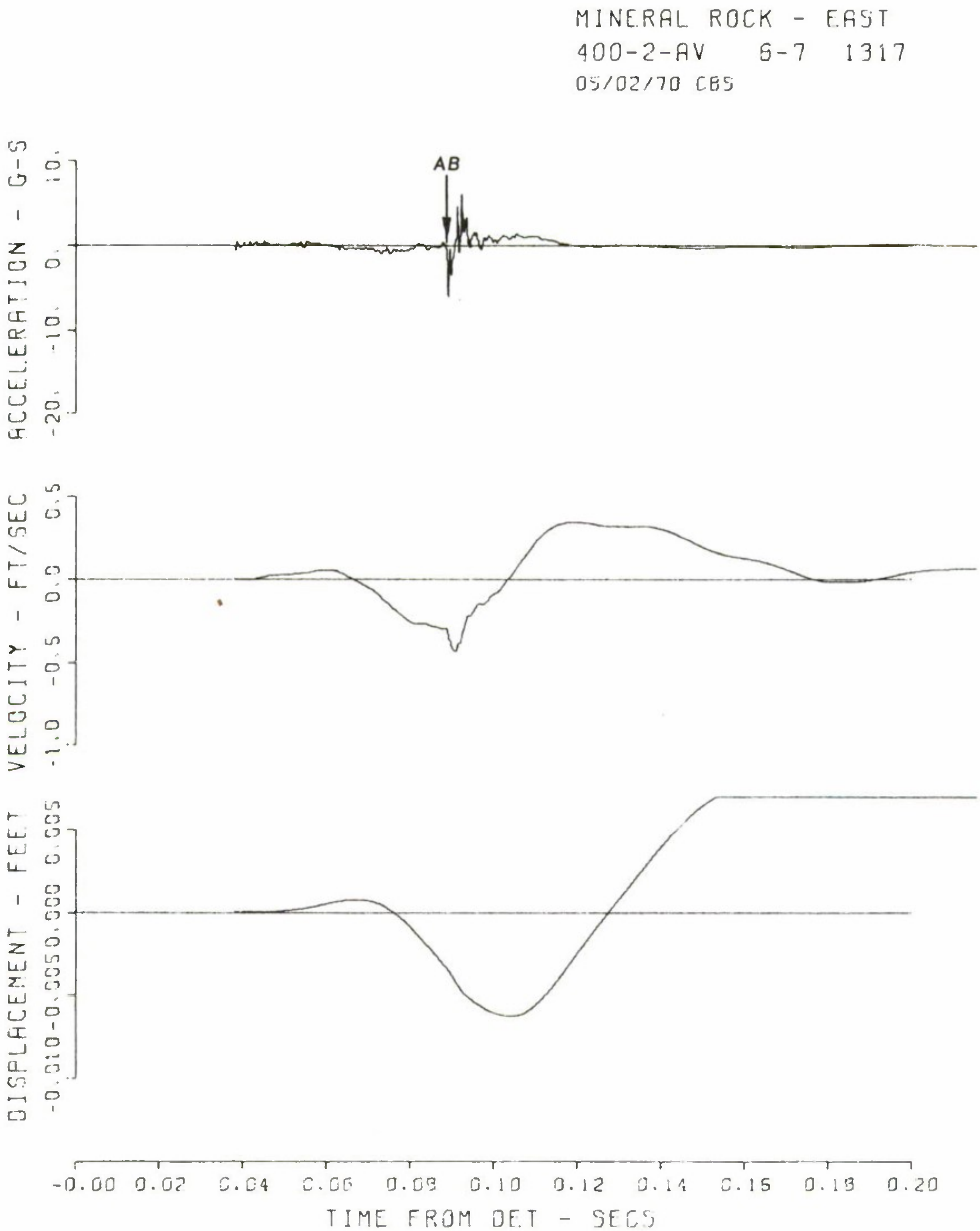


Figure A.23 Gage 400-2-AV.

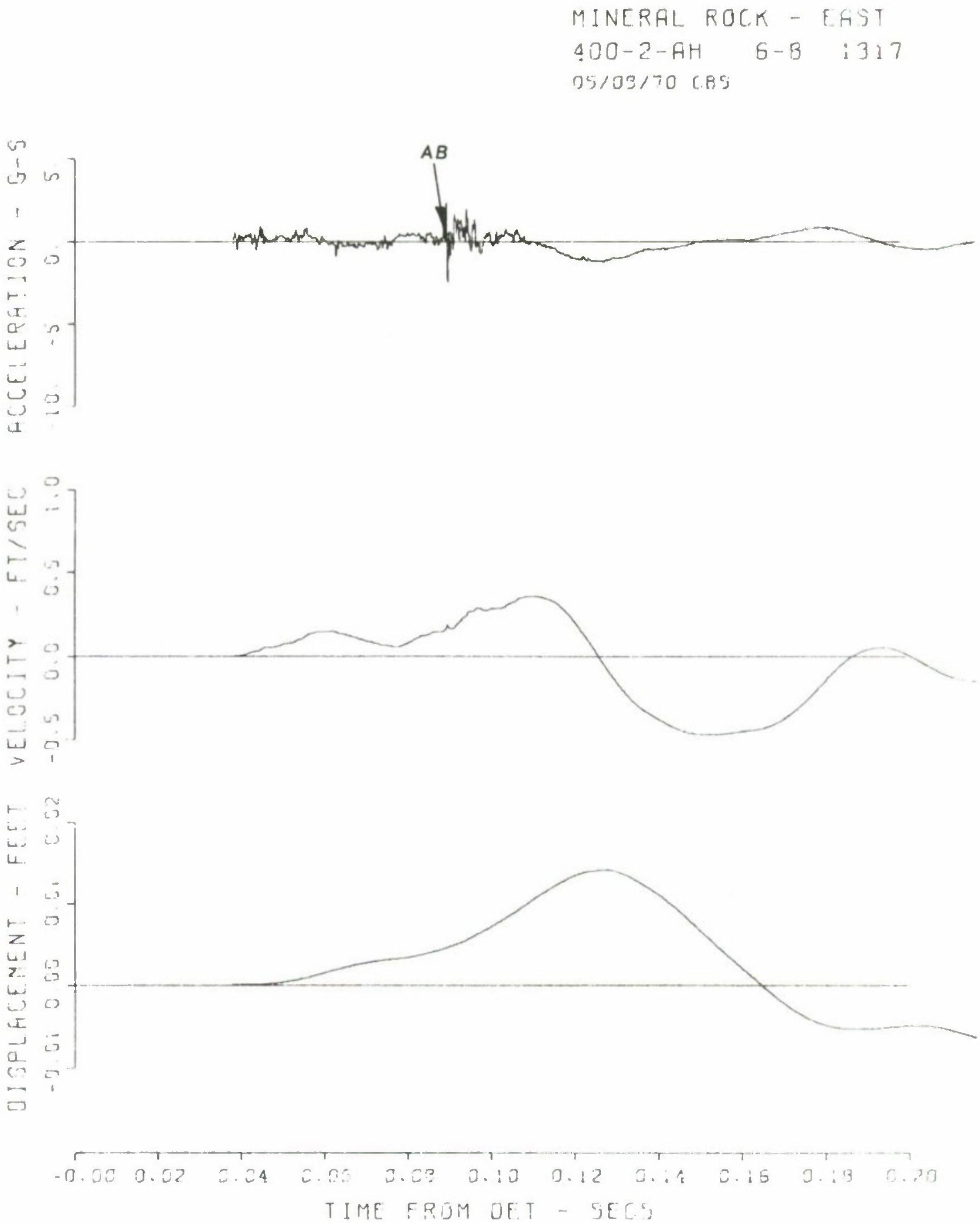


Figure A.24 Gage 400-2-AH.

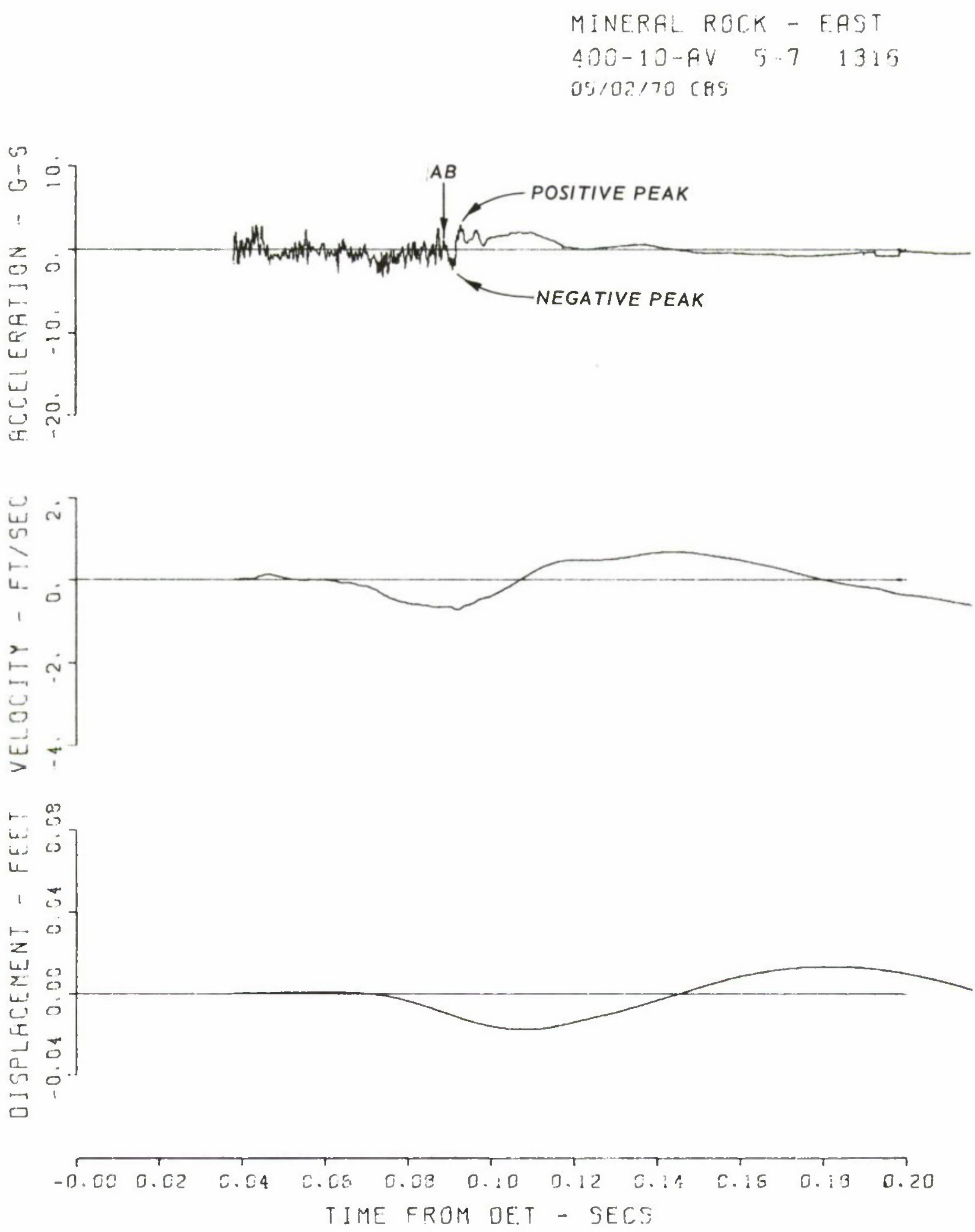


Figure A.25 Gage 400-10-AV.

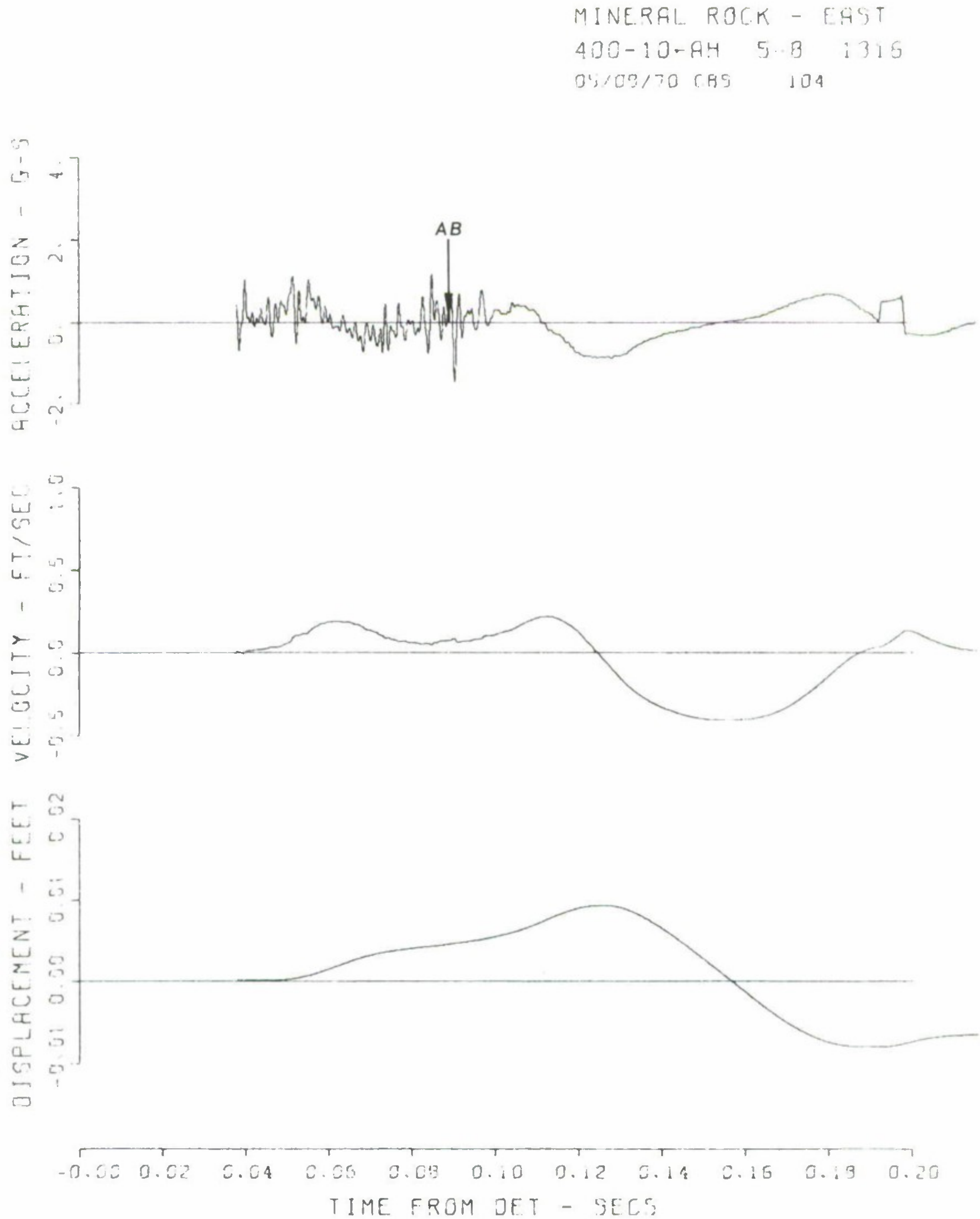


Figure A.26 Gage 400-10-AH.

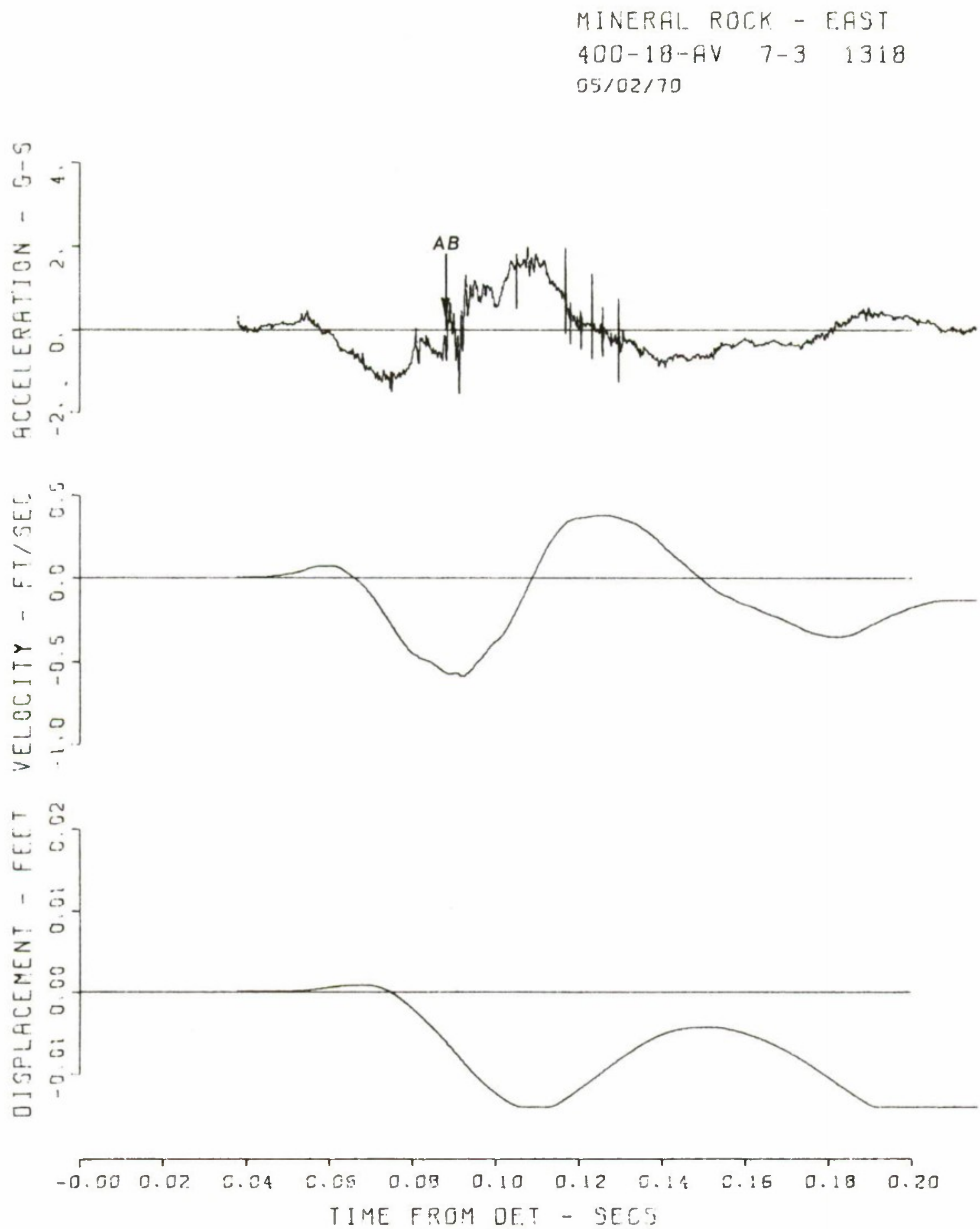


Figure A.27 Gage 400-18-AV.

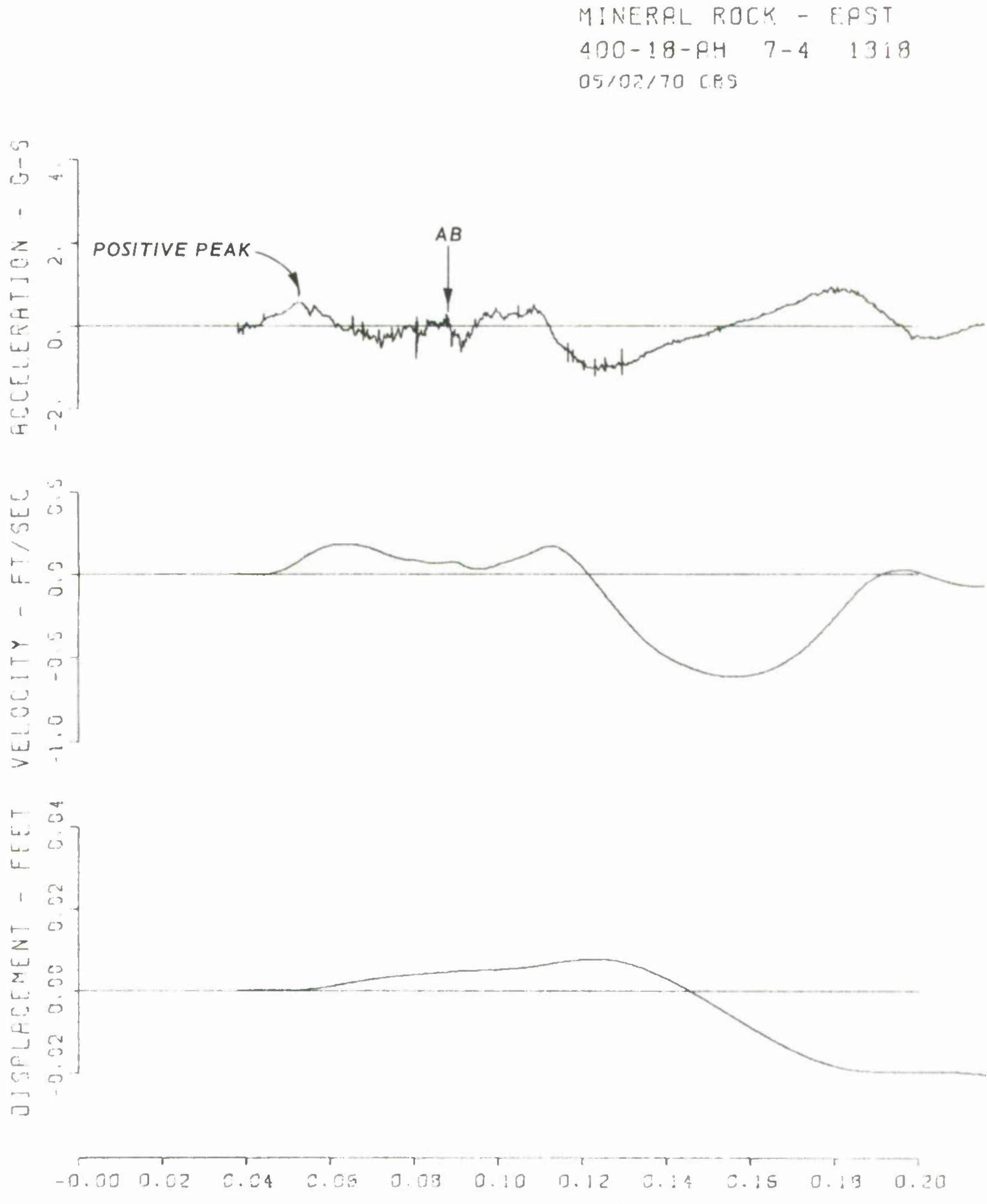


Figure A.28 Gage 400-18-AH.

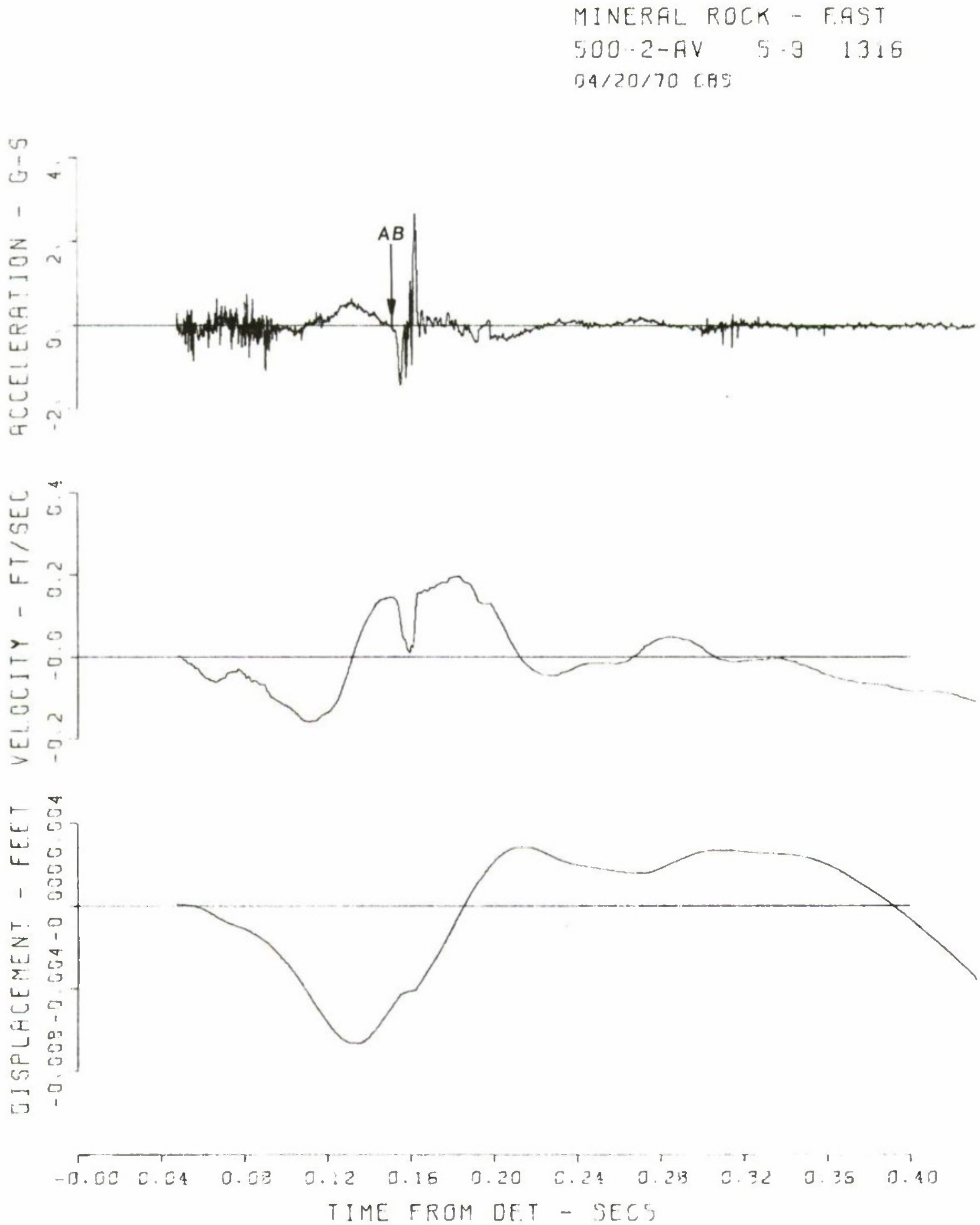


Figure A.29 Gage 500-2-AV.

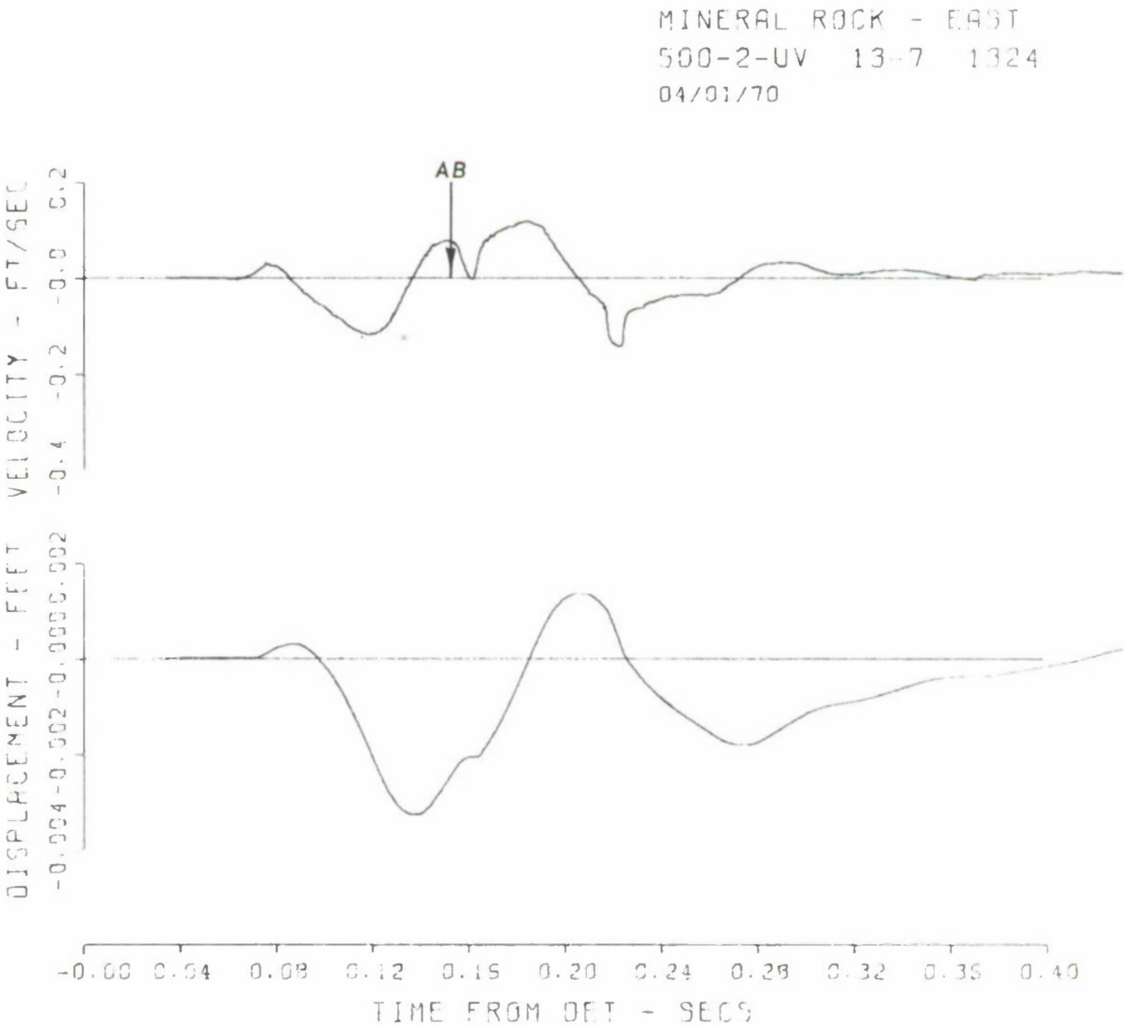


Figure A.30 Gage 500-2-UV,

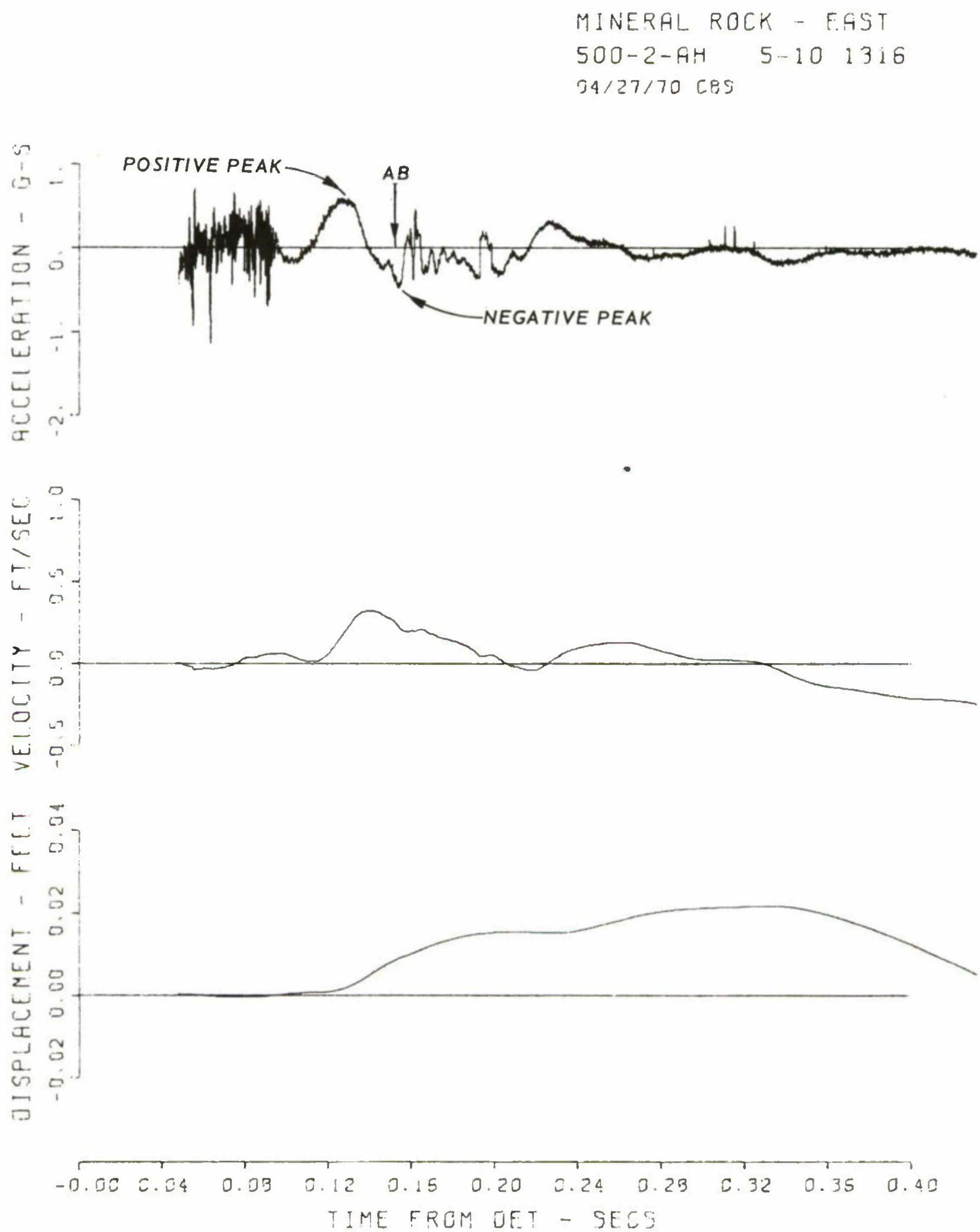


Figure A.31 Gage 500-2-AH.

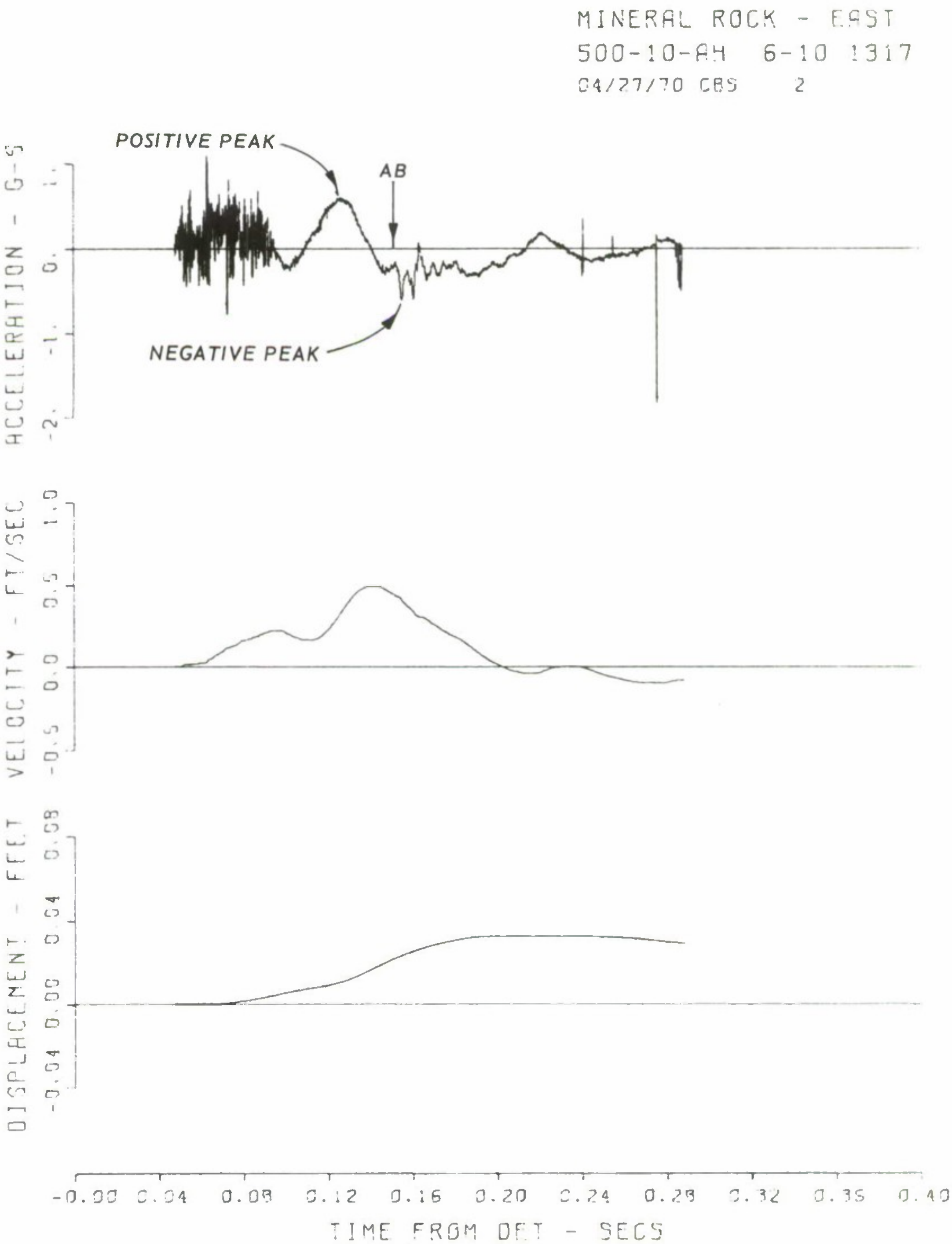


Figure A.32 Gage 500-10-AH.

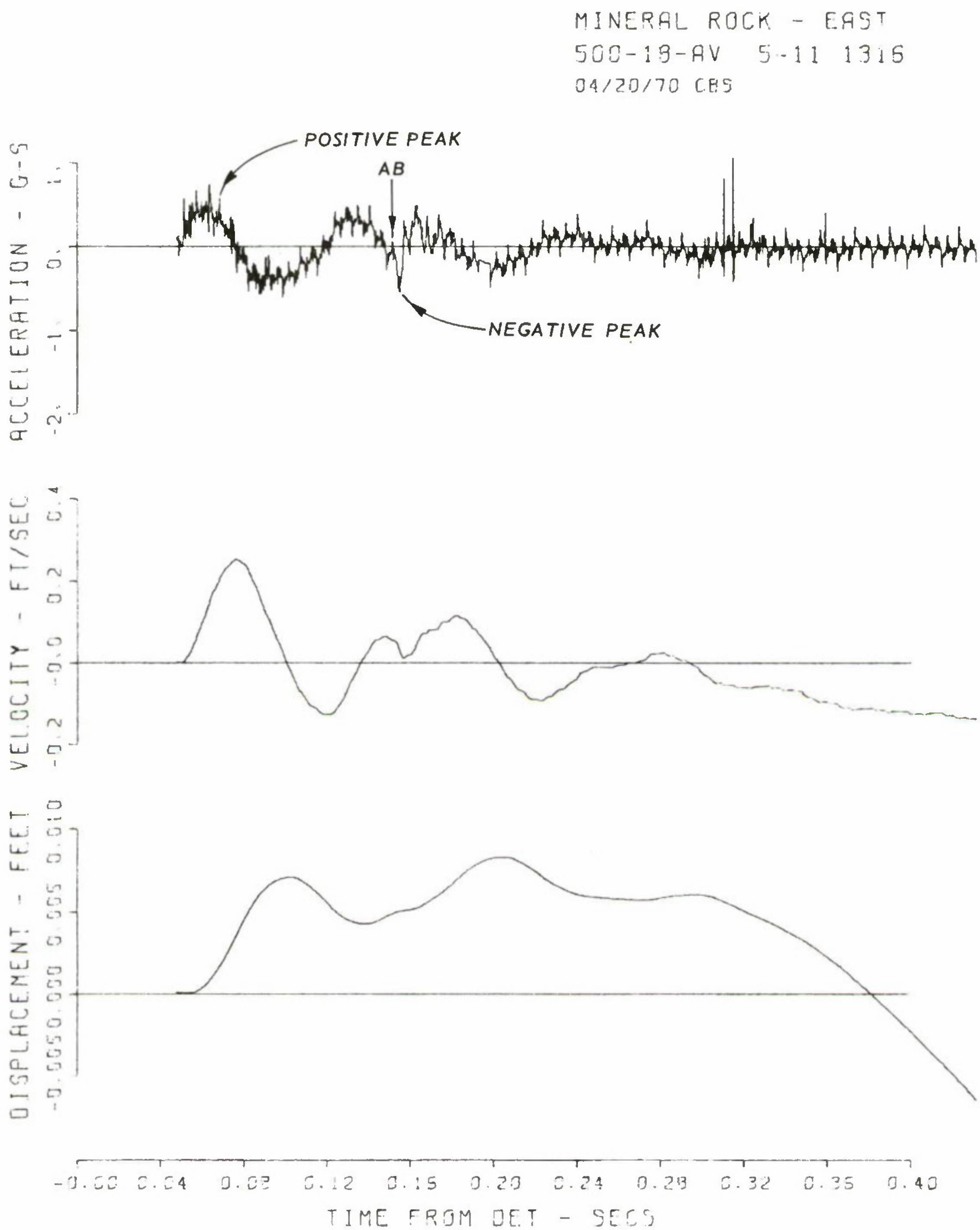


Figure A.33 Gage 500-18-AV.

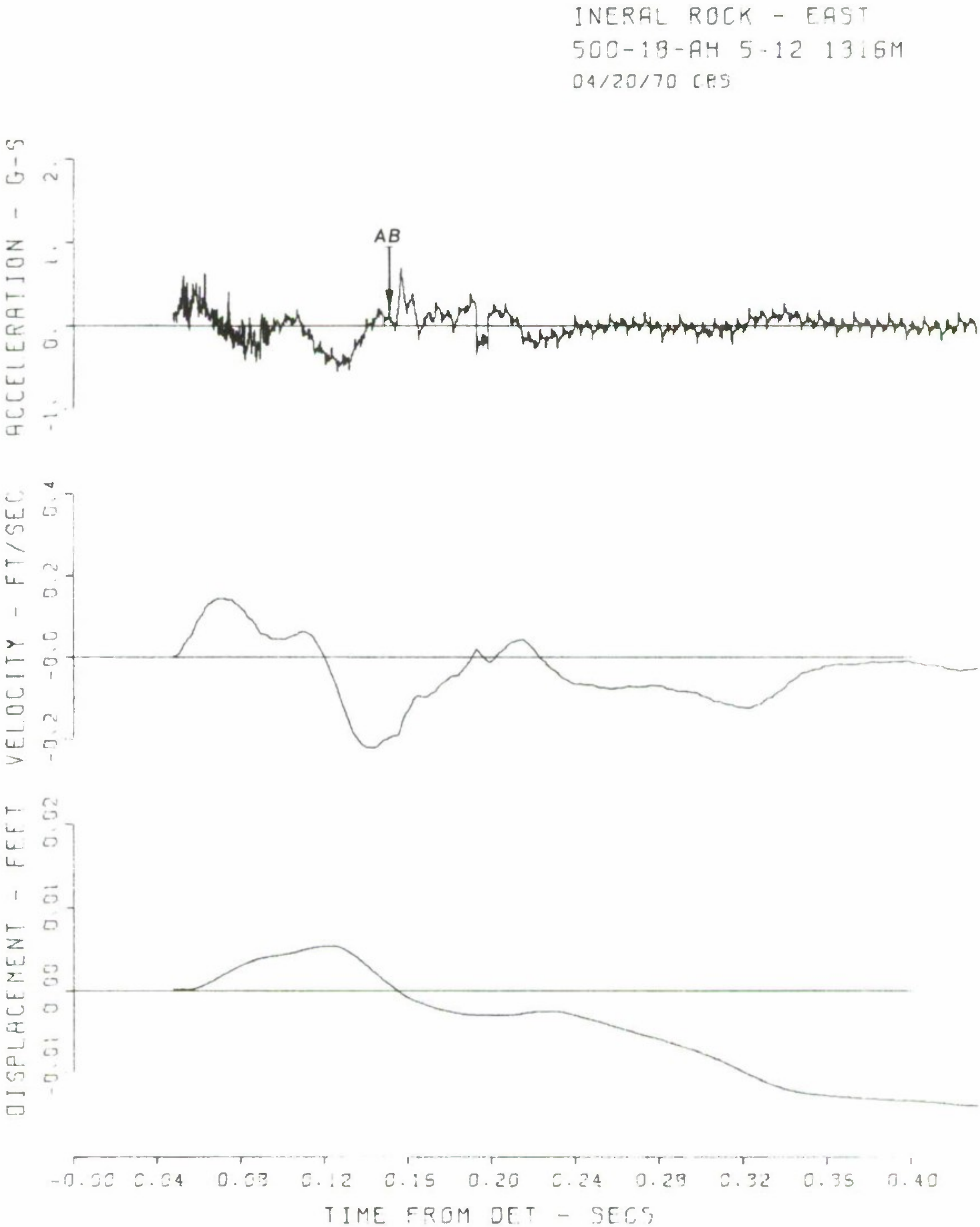


Figure A.34 Gage 500-18-AH.

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13. ABSTRACT

The objectives of this study were to measure all ground motions in the outrunning region produced by the Mineral Rock Event of Operation Mine Shaft. The Mineral Rock Event was a duplication of the Mine Ore Event of the same series, and was a 100-ton sphere of TNT placed with the center of gravity 0.9 charge radius (about 7.2 feet) above the ground surface. Accelerometers and velocity gages were installed from 200 to 500 feet from ground zero at depths of 2, 10, and 18 feet. Time histories of all successfully recorded gages are presented in Appendix A along with integrals of each record. The outrunning acceleration data were partially obscured by a cable noise problem. This noise was blast overpressure-induced and unfortunately was present during the significant outrunning motion onset, i.e., before airblast arrival at the gage locations. Although these data are limited, they are discussed along with the outrunning velocity data. Airblast-induced motions are treated in detail. Vertical airblast-induced accelerations were found to attenuate rapidly with distance and depth from the maximum downward acceleration of 32 g's at the 200-foot range and 2-foot depth. These accelerations were correlated with overpressure, and, for the 2-foot depth, acceleration-to-overpressure ratios averaged 0.2 g/psi, which is considerably less than for a similar detonation over soil. Vertical particle velocities also attenuated with distance and depth from the maximum value of 1.3 ft/sec at the 200-foot range and 2-foot depth. Horizontal velocities followed much the same pattern, with a peak value of 2 ft/sec at the same location. Outrunning motion was noted on all horizontal velocity gage records. For the vertical component, outrunning motion was not apparent at the 250-foot range, but was of significant magnitude at the 500-foot range. Vertical downward displacements of a high confidence level were limited to the 250-foot range and were found to be 0.0060 to 0.0075 foot. Horizontal displacements were successfully computed from acceleration and velocity records, and at the 250-foot range were three to four times as large as the vertical displacements.

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